UNIVERSITÉ DES ANTILLES ET DE LA GUYANE

HABILITATION À DIRIGER DES RECHERCHES

Soutenance publique le : 4 novembre 2010

Sujet :

Influence des systèmes de culture bananiers en milieu volcanique tropical sur la dispersion des pesticides aux différentes échelles de l'espace agricole.

Par Dr. Philippe CATTAN

Composition du jury :

Rapporteurs :

- Philippe ACKERER, Directeur de Recherche, CNRS, LHyGeS, Strasbourg
- Jean Louis MANSOT, Professeur, Université Antilles Guyane, Pointe à Pitre
- Yves-Marie CABIDOCHE, Directeur de Recherche, INRA, Petit-Bourg

Examinateurs :

- Yves-Marie CABIDOCHE, Directeur de Recherche, INRA, Petit-Bourg
- Jean Louis MANSOT, Professeur, Université Antilles Guyane, Pointe à Pitre
- Roger MOUSSA, Directeur de Recherche, INRA, LISAH, Montpellier
- Harry OZIER-LAFONTAINE, Directeur de Recherche, INRA, Petit-Bourg
- Pascal SAFFACHE, MdC HDR, Université Antilles Guyane, Pointe à Pitre

Chapître 1. CV

1 Etat Civil

Nationalité :	Française
Date de naissance :	30 juillet 1958
Situation familiale :	Marié – 4 enfants
Adresse professionnelle :	Station de Neufchâteau – Sainte Marie 97130 Capesterre Belle Eau
Profession :	Chercheur en agronomie et hydrologie
Fonction :	Responsable des études sur l'évaluation de l'impact environnemental des pratiques agricoles en zone bananière aux échelles de la parcelle et du bassin versant.
Compétences scientifiques :	⇨ Analyse de l'impact des systèmes de culture sur le fonctionnement hydrologique et les transferts aux échelles de la parcelle et du bassin versant. Analyse de la variation spatiale et temporelle des propriétés hydrodynamiques des sols, du drainage et du ruissellement. Effet de la redistribution de la pluie par le couvert. Evaluation du transport de polluants et de la pollution des ressources en eau. Métrologie des flux de drainage et ruissellement. Démarche de modélisation adossée aux mesures in situ. Evaluation des impacts environnementaux ⇨ Analyse des pratiques au sein des exploitations agricoles. ⇨ Analyse de l'élaboration du rendement des végétaux
Thématiques :	Agronomie, hydrologie, agro-physiologie
Région(s) d'expérience :	Antilles Françaises (Guadeloupe) ; Afrique soudano-sahélienne (Sénégal, Burkina Faso)
Formation :	Diplôme d'Agronomie Approfondie (Ecole Nationale Supérieure Agronomique de Montpellier) Docteur de l'Institut National Agronomique de Paris Grignon
Compétences linguistiques :	Anglais

2 Expérience professionnelle :

2.1 Parcours

1985 recrutement au CIRAD, département IRHO

1er Phase 1985-1998 en Afrique Soudano-Sahélienne – Elaboration du rendement des oléagineux à croissance indéterminée

1985-1987 Sénégal, chercheur agronome au sein de l' ISRA (Institut Sénégalais de Recherche Agricole) à Kaolack.

- ⇨ Responsable du projet CEE sur la fertilisation économique de l'arachide au Sénégal.
- ⇨ Diagnostic de nutrition minérale sur réseau de placettes chez les producteurs ; zonage. Essais agronomiques chez les producteurs. Enquêtes sur les systèmes de culture.

1987-1998 Burkina Faso, chercheur en agronomie des protéagineux au sein du programme Protéagineux de l'INERA (Institut de Recherche Agronomique du Burkina Faso).

- ⇨ Responsable d'équipe.
- ⇨ Responsable administratif du CIRAD IRHO au Burkina de 1987 à 1992.
- ⇨ Etude de l'incidence des conditions de milieu soudano-sahéliennes, caractérisées par une forte compétition pour l'eau et les éléments minéraux, sur les relations entre les techniques culturales (notamment la fertilisation, les densités et les dates de semis) et la production de matière sèche. Réseau d'essais multilocaux ; essais agronomiques en station ; essais de longue durée.
- ⇨ Développement de recherches en agrophysiologie sur l'élaboration du rendement de l'arachide et du sésame. Etude de l'ombrage, des stress hydriques et des variétés. Participation à deux Actions Thématiques Programmées du CIRAD en 1995-1996 (Modèles de croissance et

développement des cultures annuelles ; Influence des facteurs trophiques sur la mise en place et le maintien des organes reproducteurs constituant les composantes du rendement chez quelques espèces tropicales).

1996 Soutenance de thèse sur l'élaboration du rendement de l'arachide

2e Phase 1998-2009 en Guadeloupe. Evolution Thématique : mise en œuvre et développement d'un programme de recherche sur l'évaluation des impacts environnementaux des systèmes de culture bananiers.

Responsable d'une équipe comprenant 1 technicien et 1 collaborateur, ainsi que le personnel non permanent affecté à l'opération (VCAT, stagiaires)

Etude des flux de pesticide à l'échelle de la parcelle (40% des activités)

- ⇨ caractérisation de la redistribution de la pluie par le couvert végétal
- ⇨ étude des facteurs de déclenchement du ruissellement
- ⇨ variabilité spatiale du drainage en parcelle
- ⇨ dispersion des pesticides : transport dans les eaux de drainage et de ruissellement ; variabilité spatiale et temporelle ; transport préférentiel ; bilan.
- ⇨ comportement des molécules dans les sols

Etude des flux de pesticide à l'échelle du bassin versant (30% des activités)

- ⇨ caractérisation du fonctionnement hydrologique d'un bassin versant tropical sur sol volcanique
- ⇨ modélisation spatialisée des flux hydriques
- ⇨ dispersion d'un pesticide : contamination des réserves en eau souterraines et superficielles ; pollutions événementielles et diffuses.

Etude des pratiques agricoles (20% des activités)

- ⇨ connaissance et déterminants des pratiques : diagnostic territorial ; déterminant des pratiques de jachère, alternative à la lutte chimique ; déterminants de l'évolution des surface en banane sur un petit bassin versant
- ⇨ évaluation des pratiques : réflexion sur une méthode de diagnostic environnemental de bananeraies pour la zone de montagne guadeloupéenne ; synthèse de connaissances aboutissant à l'établissement de fiches environnementales des cultures

Innovations techniques pour réduire les impacts environnementaux (10% des activités)

- ⇨ évaluation d'un système de type « biobed » pour la dégradation des molécules pesticides présentes dans les eaux de rinçage des pulvérisateurs ainsi que des bouillies fongicides en sortie de hangar d'emballage

2.2 Encadrement scientifique et formation

(N.B. : les références des publications/communications réalisées avec les personnes encadrées sont indiquées entre crochet – cf numérotation partie 3.)

Thèse

- ⇨ Jean-Baptiste Charlier 2004-2007, co-encadrement avec Roger Moussa (directeur de thèse, INRA, UMR LISAH, Montpellier) : Fonctionnement et modélisation hydrologique d'un petit bassin versant cultivé en milieu volcanique tropical. **[11] [15] [16] [17] [26] [48] [50] [54]**
- ⇨ Lai Ting PAK 2008-2011, co-encadrement avec François Colin((SupAgro, UMR LISAH, Montpellier) et Marc Voltz (directeur de thèse, INRA, UMR LISAH, Montpellier) d'une thèse sur la Modélisation hydrologique distribuée des transferts de pesticides en zone bananière antillaise à l'échelle de bassins versants : application à l'évaluation de l'impact des pratiques agricoles sur la contamination des ressources

en eau et à la recherche de stratégies de prévention par modification de la répartition des systèmes de culture. **[58] [62]**

DEA, DAA, Master 2

- ➪ Perpina C. 2001 (DAA de l'INH Anger)
- ➪ Berger A. 2002 (DAA ENSAM Montpellier)
- ➪ Le Doze S. 2004 (DEA INA PG)
- ➪ Lazrak El Guali 2005 (DEA INA PG)
- ➪ Desbois P. 2006 (DAA Agrocampus Rennes) **[15]**
- ➪ Stephan X. 2006 (Master2 Institut d'Etudes du Développement Economique et Social)
- ➪ Lapeyre L. 2007 (Master2 Université d'Orléans)

Autres formations

- ➪ Guinde L. 1999 (Maîtrise UAG)
- ➪ Nouvelon A. 1999 (Diplôme d'Ingénieur de fin d'études ISTOM) **[8]**
- ➪ Amoravain V. 2000 (Diplôme d'Ingénieur de fin d'études du CNEARC)
- ➪ Gouyer S. 2000 (Diplôme d'Ingénieur de fin d'études ISTOM)
- ➪ Champoiseau A. 2001 (Diplôme d'Ingénieur de fin d'études ISTOM)
- ➪ Labas J. 2002 (Diplôme d'Ingénieur de fin d'études ISTOM)
- ➪ Martin J. 2004 (DESS Avignon)
- ➪ Heuzé S. 2005 (ISIM Montpellier)
- ➪ Fresu T. 2005 (Université de Milan)
- ➪ Cavasino A. 2005 (Diplôme d'Ingénieur de fin d'études ISTOM)
- ➪ Félicité O. 2006 (Diplôme d'Ingénieur de fin d'études Polytech Orléans)
- ➪ Feltz N. 2008 (Diplôme d'Ingénieur de l'Université Catholique de Louvain)

- ⇨ Germeau M. 2009 (Diplôme d'Ingénieur de l'Université Catholique de Louvain) **[61]**

Volontaires à l'aide technique – jeunes chercheurs

- ⇨ Gardet O. 1998-1999 (VCAT)
- ⇨ Tixier P. 1999-2000 (VCAT)
- ⇨ Simon A. 2000-2001 (VCAT)
- ⇨ Lacas JG. 2001-2002 (VCAT) **[6] [9] [39] [42]**
- ⇨ Lefevre C. 2002-2003 (VCAT)
- ⇨ Charlier J.-B. 2003-2004 (VCAT)

- ⇨ Rousseau M. 2005 Post doctorant
- ⇨ Levillain J. 2009 CDD jeune chercheur

Comités de pilotage

- ⇨ membre du comité de pilotage de la thèse de Céline Bassette : Modélisation de l'interception de la pluie par le bananier (INRA APC, encadrant F. Bussière, INRA APC, Guadeloupe)
- ⇨ membre du comité de pilotage de la thèse Julie Sansoulet : Transfert d'eau et de solutés dans un Andosol sous culture bananière (INRA APC, encadrant Y.-M. Cabidoche, INRA APC, Guadeloupe)
- ⇨ membre du comité de pilotage du post-doctorant Marine Rousseau : Modélisation du transfert de pesticides dans le sol à l'échelle local. (CIRAD AMIS, encadrant S. Marlet, UMR G-Eau, Montpellier)

Jury de thèse

- ⇨ membre du jury de thèse de Julie Sansoulet : soutenance le 29 janvier 2007
- ⇨ membre du jury de thèse de Jean-Baptiste Charlier : soutenance le 18 décembre 2007
- ⇨ membre du jury de thèse de Sophie Coat : soutenance le 18 juin 2009

Activité d'enseignement

- ⇨ 1999-2001 cours en maîtrise d'agronomie tropicale à l'UAG
- ⇨ à partir de 2005, TD annuels à l'Université Antilles Guyane dans le cadre du DEA Environnement Tropical et Valorisation de la Biodiversité.

2.3 Partenariat

Institutionnel

- ⇨ 1999 - DIREN Guadeloupe (partenaire institutionnel sur les questions environnementales en Guadeloupe)
- ⇨ 1999 - SICA de producteurs de banane

Hydrologie et comportement des pesticides

- ⇨ 1999 - partenariat INRA APC : fonctionnement hydrologique de la bananeraie à l'échelle de la parcelle ; pollutions à la Chlordécone
- ⇨ 2000 - partenariat avec l'UMR LISAH : fonctionnement hydrologique de bassin versant et le transfert de pesticides
- ⇨ 2003-2006 – partenariat UPR Recyclage et Risque du CIRAD, INRA Avignon : étude du fonctionnement hydrologique de la bananeraie à l'échelle locale
- ⇨ 2003-2004 - partenariat Unité Environnement et Grandes Cultures, INRA Grignon : comportement des pesticides dans les sols
- ⇨ 2004-2007 - partenariat BRGM : écoulements souterrains en milieu volcanique
- ⇨ 2008 - Université Catholique de Louvain : relation entre caractéristiques hydrodynamiques des sols et pédologie.

Innovations techniques

- ⇨ 2006-2007 - UPR Production Fruitière, CIRAD : recherche en partenariat sur l'évaluation de l'efficacité d'un dispositif de dépollution des eaux de rinçage des pulvérisateurs (système biobed)

Pratiques agricoles

- ⇨ 1999-2007 - UMR TETIS, Montpellier : appui à la caractérisation du fonctionnement des exploitations agricoles

Organismes aquatiques

- ⇨ 2008 - partenariat en cours avec l'Université Antilles Guyanes sur l'évaluation de l'impact de la Chlordécone sur les organismes dulçaquicoles.

2.4 Projets

- ⇨ 2000-2006 participant du projet DOCUP : programme opérationnel sur la filière banane. Fonds Europe, Etat, Région.
- ⇨ 2001-2002 participant du projet BANENVI : Fonctionnement hydrologique redistributif du système bananier - Andosol cultivé. Conséquences sur les stockages et flux d'intrants solubles localisés. Fonds INRA/CIRAD.
- ⇨ 2001-2003 *proposant et coordonnateur* en Guadeloupe du projet DIREN1 : Etude des risques de pollution d'origine agricole en Martinique et en Guadeloupe : Gestion des transferts (eau, sol, produits phytosanitaires et engrais) à l'échelle du bassin versant. Pour la Guadeloupe financement Europe, Etat, Région.
- ⇨ 2004-2007 *proposant et coordonnateur* du projet DIREN2 : Gestion des risques environnementaux liés à l'activité agricole à l'échelle du bassin versant dans la zone bananière guadeloupéenne. Financement Europe, Etat, Région.
- ⇨ 2003-2006 participant du projet PNRH : Etude et modélisation à l'échelle locale des transferts 3D de l'eau de pluie concentrée par le bananier à la surface d'un Andosol. Financement PNRH.
- ⇨ 2004-2005 Participant du projet MEDD : Stockage dans les sols à charges variables et dissipation dans les eaux de zoocides organochlorés autrefois appliqués en bananeraies aux Antilles : relation avec les systèmes de culture. Financement Ministère de l'Ecologie et du Développement Durable (MEDD).

- ⇨ 2005-2008 participants au projet Innovations agro-écologiques et organisationnelles pour une Gestion Durable de la Qualité de l'Eau (GeDuQuE) dans des régions de monoculture à forts niveaux d'intrants phytosanitaires. Financement ANR-ADD.
- ⇨ 2007 *proposant et coordonnateur* du projet BIOBED : Efficacité d'un système biobed pour le traitement des bouilles fongicides en sortie de hangar d'emballage des bananes. Financement Etat.
- ⇨ 2007 participant à la rédaction du projet AGROECOTROP : Agroécologie des systèmes multi-espèces proposé dans le cadre du programme opérationnel 2007-2013 Guadeloupe. Fonds Europe, Etat, Région
- ⇨ 2008 *coordination* du projet CHLORDEXCO (réponse à l'appel à projet CES de l'ANR 2008) « Pollution des sols et des eaux par la Chlordécone aux Antilles, conséquences sur la contamination des cultures et des organismes dulçaquicoles »

2.5 Conception, mise en œuvre et coordination des activités sur le dispositif expérimental traitant de l'analyse des transferts en Guadeloupe

Mise en œuvre et suivi d'une parcelle de référence à Neufchâteau

- ⇨ étude de l'effet des systèmes de culture sur les transferts hydriques et des polluants associés.
- ⇨ équipement : 18 systèmes de mesure de l'intensité pluviométrique au sol ; 4 canaux venturi, 4 débitmètres, 2 préleveurs automatiques, 2 centrales d'acquisition de données (Campbell), 8 lysimètres, 1 caméra vidéo asservie à la pluie pour visualiser le déclenchement du ruissellement et les surfaces contributives à ce ruissellement, tensiomètres
- ⇨ mesure chroniques de ruissellement et d'infiltration ; analyses pesticides des eaux et des sols
- ⇨ Accueil des dispositifs expérimentaux des projets INRA/CIRAD (2001-2002), Etat Région (2001-2003 et 2004-2007), PNRH (2003-2006) ;

post-doctorat de Marine Rousseau (UMR G-EAU) ; thèse de Julie Sansoulet (INRA).

Mise en œuvre et suivi d'un bassin expérimental de référence de 20 hectares

- ⇨ étude et suivi hydrologique (nappe et rivière) et dispersion des produits phytosanitaires.
- ⇨ équipement : 1 seuil en sortie de bassin équipé d'un débitmètre et d'un préleveur automatique ; 4 pluviomètres à acquisition automatique 18 piézomètres superficiels (<4m) et 8 forages profonds (10 à 50 m) dont 12 en acquisition automatique.
- ⇨ mesures : FLUX (chroniques pluviométriques, débitmétriques, piézométriques) ; CARACTERISATION (couches géologiques ; relevés altimétriques géoréférencés au GPS pour réalisation d'un Modèle Numérique de Terrain ; caractéristiques hydrodynamiques des sols ; propriétés hydraulique de la zone saturée ; relevés microtopographiques ; évolution de l'occupation du sol) ; FONCTIONNEMENT (traçage à l'aide d'un nématicide).
- ⇨ Accueil des dispositifs expérimentaux des projets Etat-Région (2001-2003 et 2004-2007), MEDD (2004-2005), et à terme du projet ANR CES Chlordécone. Support de la thèse de Charlier (2004-2007).

Caractérisation d'un bassin expérimental 400 hectares

- ⇨ étude et suivi des exploitations agricoles, des pratiques culturales et des impacts environnementaux.
- ⇨ mesures : Diagnostic agro-écologique en 2001. Enquêtes sur la Gestion de l'assolement et sur l'Analyse des trajectoires d'évolution des exploitations bananières. Diagnostic de type CORPEN en 2007. Typologie de bassin versant en 2007.
- ⇨ fonction : Bassin de référence pour les projets Etat-Région (2001-2003 et 2004-2007), ANR GeDuQuE (2005-2008) et ANR CES CHLORDEXCO. Bassin Pilote pour la DIREN depuis 2007.

2.6 Activités d'animations sur les impacts environnementaux

- ⇨ mise en œuvre des réunions de programmation dans le cadre des projets coordonnés
- ⇨ organisation des restitutions auprès des différents acteurs du milieu agricole : séminaires de restitutions avec intervenants extérieurs auprès de l'ensemble des acteurs du monde agricole (tous les deux ans avec invitation de la presse régionale) ; communication auprès de la profession bananière ; communication et participation au Groupe Régional d'Etude de la Pollution par les produits Phytosanitaires (GREPP) (3 à 4 fois par an) ; communication auprès des élus de la région (commission environnement) ;
- ⇨ participation aux comités d'expertise réuni par divers institutionnels : mise en œuvre de la Directive Cadre sur l'Eau ; périmètres de captages ; SDAGE de la Guadeloupe

2.7 Formations suivies :

- ⇨ 2001 animation d'équipe
- ⇨ 2003 statistiques spatiales
- ⇨ 2006 gestion de projets
- ⇨ 2006 écriture scientifique en anglais (1ère partie)
- ⇨ 2007 écriture scientifique en anglais (2ème partie)
- ⇨ 2007 formateur occasionnel
- ⇨ 2009 séminaire Réflexives encadrants-doctorants
- ⇨ 2009 statistiques sous R

3 Publications :

3.1 Articles de périodiques :

3.1.1 Articles publiés dans les revues à facteur d'impact

[1] **Cattan**, P. Fleury, A. (1998). Flower production and growth in the groundnut plants. European Journal of Agronomy (IF 2007 1,503), 8, p 13-27.

[2] Zagre B., Balma D., **Cattan** P. (1999). Analyse diallèle du poids de mille graines chez le sésame (*Sesamum indicum* L.). Cahiers/Agricultures (IF 2007 0,128), 8, 118-122

[3] **Cattan**, P., Letourmy, P., Zagre, B. (2001). Rendement de l'arachide et du sorgho en rotation sous différents itinéraires techniques au Burkina Faso. Cahiers/Agricultures (IF 2007 0,128), 10, 159-172

[4] Dulcire, M., **Cattan**, P. (2002). Monoculture d'exportation et développement agricole durable : cas de la banane en Guadeloupe. Cahiers/Agricultures (IF 2007 0,128), 11, 313-321.

[5] Bonin M., **Cattan** P. (2006) Pratiques de jachère et dispositifs d'appui en production bananière guadeloupéenne. Fruits (indexation ISI en cours), 60, 2, p 83-98.

[6] **Cattan**, P., Cabidoche, Y.-M., Lacas, J.G, Voltz, M. (2006). Effects of tillage and mulching on runoff under banana (Musa spp.) on a tropical Andosol. Soil and Tillage Research (IF 2007 1,846). Vol 86, p 38-51.

[7] Sansoulet, J., Cabidoche, Y.-M., **Cattan**, P. (2007). Adsorption and transport of nitrate and potassium in an Andosol under banana (Guadeloupe, French West Indies). European Journal of Soil Science.58 (IF 2007 2,73), p 478-489.

[8] **Cattan**, P., Bussière, F., Nouvellon, A. (2007) Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation. Hydrological Processes (IF 2007 1,798). Vol 21, p 2196-2205.

[9] **Cattan**, P., Voltz, M., Cabidoche, Y.-M., Lacas, J.G, Sansoulet, J. (2007) Spatial and temporal variations in percolation fluxes in a tropical Andosol influenced by banana cropping patterns. Journal of Hydrology (IF 2007 2,161), vol 335: n° 1-2, 157-169.

[10] Sansoulet, J., Cabidoche, Y.-M., **Cattan**, P., Ruy, S., Simunek, J. (2008). Spatially Distributed Water Fluxes in an Andisol under Banana Plants: Experiments and Three-Dimensional Modeling. Vadose Zone Journal (IF 2007 1,55).7(2), p 819-829.

[11] Charlier, J.-B., **Cattan**, P., Moussa, R., and Voltz, M. (2008) Hydrological behaviour and modelling of a volcanic tropical cultivated catchment. Hydrological Processes (IF 2007 1,798), p 4355-4370.

[12] De Roffignac, L., **Cattan**, P., Mailloux, J., Herzog, D., Le Bellec, F. (2008) Efficiency of a bagasse substrate in a biological bed system for the degradation of glyphosate, malathion and lambda cyhalothrin under tropical climate. Pest Management Science (IF 2007 1,867), vol 64, n°12, p. 1303-1313.

[13] Saison, C., **Cattan**, P., Louchart, X., Voltz, M. (2008) Effect of spatial heterogeneities of water fluxes and application pattern on Cadusafos fate on banana cultivated Andosols. Journal of Agricultural and Food Chemistry (IF 2007 2,532), vol 56, p. 11947-11955.

[14] Cabidoche, Y.-M., Achard, R., **Cattan**, P., Clermont-Dauphin, C., Massat, F., Sansoulet, J. (2009). Long term pollution by chlordecone of tropical volcanic soils in the French West Indies: a simple leaching model accounts for current residue contents. Environmental Pollution (IF 2007 3.135), vol 157, p 1697-1705.

[15] **Cattan** P., Ruy, S., Cabidoche, Y.-M, Findeling, A., Desbois, P., Charlier, J.-B. (2009). Effect on runoff of rainfall redistribution by the impluvium-shaped canopy of banana cultivated on an Andosol with a high infiltration rate. Journal of Hydrology (IF 2007 2.161), vol 368, p. 251-261.

[16] Charlier, J.-B., **Cattan**, P., Moussa, R., and Voltz, M. (2009). Transport of a Nematicide in Surface and Ground Waters in a Tropical Volcanic Catchment. Journal of Environmental Quality (IF 2007 2.331), vol 38, p 1031-1041.

[17] Charlier, J.-B., Moussa, R., **Cattan**, P. and Voltz, M. (2009). Modelling runoff at the plot scale taking into account rainfall partitioning by vegetation: application to stemflow of banana (Musa spp.) plant. Hydrol. Earth Syst. Sci. (IF 2007 2.167), 13(11), p 2151-2168.

3.1.2 Articles publiés dans les revues à comité de lecture, sans facteur d'impact

[18] De Roffignac, L., **Cattan**, P., Mailloux, J., Herzog, D., Le Bellec, F. (2007). Un biobed à la bagasse testé en Guadeloupe : expérimentation d'un dispositif de gestion d'effluents phytosanitaires agrumicoles sur l'exploitation. Phytoma – La défense des végétaux. Vol 606, 4-7.

3.1.3 Autres Articles

[19] Schilling, R., **Cattan**, P. (1991). La culture du sésame en Afrique tropicale. Oléagineux vol 46, 3, p 125-128.

[20] **Cattan**, P. (1992). Efficacité de la fertilisation phosphatée de l'arachide et du sorgho au Burkina Faso et utilisation des phosphates locaux. Oléagineux vol 47, n°4, p 171-179.

[21] **Cattan**, P., Schilling, R. (1992). Evaluation expérimentale de différents systèmes de culture incluant l'arachide en Afrique de l'Ouest. Oléagineux vol 47, n°11, p 635-644.

[22] **Cattan**, P. (1996). Les composantes du rendement de l'arachide. Agriculture et développement, n°11, p 33-38.

[23] **Cattan**, P., Zagre, B., Compaore, E., Sankara, P., Fleury, A. (2004) Influence des contraintes d'alimentation hydrique sur la mise en place des organes reproducteurs de l'arachide (Arachis hypogaea L.). Annales de l'Université de Ouagadougou, Série C, 2, 243-367.

[24] **Cattan**, P., Zagre, B., Compaore, E., Zombre, G., Sankara, P., Fleury, A. (2004) Effet de l'ombrage sur la mise en place des organes reproducteurs et les rendements de l'arachide (Arachis hypogaea L.). Annales de l'Université de Ouagadougou, Série C, 3, 1-17.

[25] Cabidoche, Y.-M., Clermont-Dauphin, C., Achard, R., Caron, A., **Cattan**, P., Chabrier, C., Lafont, A., Lesueur-Jannoyer, M., Sansoulet, J. (2008) Stockage dans les sols et dissipation dans les eaux de la Chlordécone, insecticide organochloré autrefois appliqués dans les bananeraies des Antilles Françaises. Les Cahiers de PRAM, Le Lamentin, Martinique, n°7, 39-44

[26] **Cattan**, P., Barriuso, E., Cabidoche, Y.-M., Charlier, J.-B., Voltz, M. (2008) Quelques éléments clés sur l'origine et le mode de pollution des eaux par les produits phytosanitaires utilisés en agriculture. Les Cahiers de PRAM, Le Lamentin, Martinique, n°7, 13-19.

3.2 Ouvrages

[27] **Cattan**, P. (1996). Contribution à l a connaissance du fonctionnement d'un peuplement d'arachide (Arachis hypogaea L.) : proposition d'un schéma d'élaboration du rendement. Thèse, Paris, France, INA PG, 180p.

3.3 Chapitres d'ouvrage

[28] Bonin, M., **Cattan,** P., Dorel, M., Malézieux, E., 2006. L'émergence d'innovations techniques face aux risques environnementaux. Le cas de la culture bananière en Guadeloupe : entre solutions explorées par la recherche et évolution des pratiques. In : Agronomes et Innovations, 3e édition des entretiens du Pradel. Actes du colloque des 8-10 septembre 2004. J. Caneill (ed.). L'Harmattan, Paris, 123-135

3.4 Communications de congrès

[29] **Cattan**, P., Schilling, R. (1990). Les systèmes arachidiers dans les zones de savanes ouest-africaines. in "Savanes d'Afrique, terres fertiles ?", Pieri C. (ed), Paris, Ministère de la coopération, Montpellier, 10 au 14 décembre 1990. p.145-171

[30] **Cattan**, P. (1992). Aspect de la fertilisation phosphatée de l'arachide au Burkina Faso. communication présentée à l'atelier arachide ICRISAT, Ouagadougou, septembre 92, 6 p.

[31] **Cattan**, P. (1994). Quelques éléments du diagnostic cultural chez l'arachide hâtive. Proc atelier arachide ICRISAT, Niamey, novembre 1994.

[32] Zagre, B., Balma, D., **Cattan**, P. (1996). Synthèse des résultats de la recherche sur l'arachide au Burkina Faso en amélioration génétique et en agronomie. Proc atelier arachide ICRISAT, Accra, novembre 1996.

[33] Cabidoche, Y.-M., **Cattan**, P., Dorel, M., Paillat, J.M. (2002). Intensification agricole et risque de pollution azotée des ressources en eau dans les départements français d'outre-mer insulaires : surveiller en priorité les pratiques agricoles dans les périmètres irrigués. In : Vers une maîtrise des impacts environnementaux de l'irrigation : actes de l'atelier du PCSI, 28 - 29 mai 2002, Montpellier, France. - Montpellier : CIRAD 9 pages.

[34] Dulcire, M., **Cattan**, P. (2002). The contribution of banana cultivation to sustainable development: analysis by system of activity. In Fifth IFSA European Symposium, Florence, Italy, April 8-11 2002, 440-449.

[35] Dulcire, M., **Cattan**, P. (2002). Strategic Diagnosis in an export monoculture area. In 17th Symposium of the International Farming Systems Association (IFSA), November 17-20, 2002, Orlando, Florida USA.

[36] **Cattan** P., Dulcire, M. (2003). Quelles cohabitations de la banane et des autres activités territoriales ? Recherche-action dans le croissant bananier Guadeloupéen. In : Organisation spatiale et gestion des ressources et des territoires ruraux : actes du colloque international, 25 - 27 février 2003, Montpellier, France. - Montpellier : CNEARC-SAGERT. 625-634, Français

[37] Achard, R., Cabidoche, Y.-M., **Cattan**, P., Clermont-Dauphin, C., Lassoudière, A. (2003). Stockage dans les sols à charges variables et dissipation dans les eaux de zoocides organochlorés autrefois appliqués en bananeraies aux Antilles. Relation avec les systèmes de culture (APR "Pesticides" 2002). In : Séminaire du Ministère de l'écologie et du développement durable sur l'APR pesticides, Rennes, 4-5 décembre 2003.

[38] Cabidoche, Y.-M., **Cattan,** P. (2004). Fonctionnement hydrologique distributif du système bananier - andosol cultivé. Conséquences sur les stockages et flux d'intrants solubles localisés : Fonds commun INRA/CIRAD année 2000 - Projet n°28. In : Séminaire de restitution. Appels à proposition 2000 et 2001 du fonds commun Inra-Cirad, Montpellier 7 et 8 septembre 2004. - Montpellier : CIRAD p. 14-15, Français.

[39] Lacas, J.G., Voltz, M., **Cattan**, P. (2004). Numerical evaluation of passive capillary samplers. European Geosciences Union. 1st General Assembly Nice, France, 25 - 30 April 2004.

[40] **Cattan**, P., Dulcire, M. (2004) Quelle prise en compte de l'environnement par l'activité agricole ? Gestion de la qualité des sols et des eaux par l'agriculture en zone bananière, dans le cadre d'une politique incitative. Premiers résultats. In : Regards sur les agricultures familiales et la multifonctionalité : les départements français d'outre-mer. La multifonctionnalité de l'agriculture : actes du séminaire, 21-24 novembre 2000, Bouillante, Guadeloupe. - Montpellier : CIRAD-TERA. p. 119-122.

[41] Sansoulet, J., Cabidoche, Y.-M., **Cattan,** P., Clermont Dauphin, C., Desfontaines, L., Malaval, C. (2004) Solute transfer in an andisol of the French West Indies after application of KNO3 : from the aggregate to the field experiment. In: Volcanic soil resources in Europe. COST Action 622 final meeting. Abstracts / (Eds) Hlynur Oskarsson, Olafur Arnalds. - Reykjavik: Agricultural Research Institute, 2004. - (Rala report ; n° 214)

[42] Lacas, J.G., Voltz, M., **Cattan**, P., Louchart, X. (2004). Passive capillary pan samplers: an efficient system to monitor in-situ percolation fluxes in soils. System presentation and estimation of measurement uncertainties. COST Action 629 workshop; Water pollution in natural porous media at different scales: fate, impact and indicators, Louvain- la-Neuve, Belgium, October 21-22, 2004.

[43] Bonin, M. **Cattan**, P. (2005) Les pratiques de jachère dans les exploitations bananières en Guadeloupe. In 41st Annual Meeting of the Caribbean Food Crop Society, 10-16 juillet 2005, Gosier / CFCS.

[44] Sansoulet, J., Cabidoche, Y.-M., **Cattan,** P. (2005) Modélisation des transferts de nitrates et de potassium dans un andosol sous bananeraie. In: 41st Annual Meeting of the Caribbean Food Crop Society, 10-16 juillet 2005, Gosier / CFCS

[45] Cabidoche, Y.-M., Clermont-Dauphin, C., Lafont, A., **Cattan**, P., Achard, R., Caron, A., Chabrier, C. (2005) Stockage dans les sols à charges variables et dissipation dans les eaux de zoocides organochlorés autrefois appliqués en bananeraies aux Antilles : relation avec les systèmes de culture (APR 2002). In : Pesticides : comment réduire les risques associés ? 14-16 novembre 2005, Avignon / Ministère de l'écologie et du développement durable. 6p.

[46] Sansoulet J., Cabidoche Y.-M., **Cattan** P. (2006). Modeling spatially distributed water fluxes in an andosol under banana plant: [Poster]. In: 18th World Congress of Soil Science, 9-15 juillet 2006, Philadelphia, (USA). s.l.: s.n., 1 p. World Congress of Soil Science. 18, 2006-07-09/2006-07-15, Philadelphia, USA.

[47] Bonin M., **Cattan** P., Dorel M., Malézieux E. (2006). L'émergence d'innovations techniques face aux risques environnementaux. Le cas de la culture bananière en Guadeloupe. The emergence of technical innovations in front of environmental risks. The case of the banana cultivation in Guadeloupe (FWI): between solutions explored by research and evolution of practices. In: Caneill Jacques (ed.). Agronomes et innovations : 3ème édition des entretiens du Pradel. Actes du colloque des 8-10 septembre 2004. Paris : L'Harmattan, p. 123-135

[48] Charlier, J.-B., Moussa, R., **Cattan**, P., Voltz, M. (2006). Hydrological behaviour of a small tropical catchment on volcanic deposits. In: Geophysical research abstracts. European Geosciences Union General Assembly. Vienne, Austria, 02 - 07 April 2006.

[49] De Roffignac, L., **Cattan**, P., Mailloux, J., Herzog, D., Le Bellec, F. (2006) La gestion des effluents phytosanitaires (fonds de cuve de traitement) par le système "Bioded». In : La production fruitière intégrée en Guadeloupe. Intégration de la biodiversité dans les systèmes de culture : résumés des interventions. - Montpellier : CIRAD. 1p

[50] Charlier, J.-B., Moussa, R., **Cattan**, P., Voltz, M. (2007). Hydrological modelling from the plot to the catchment scales in a tropical cultivated area. In: Geophysical research abstracts. Vol 9, European Geosciences Union General Assembly. Vienne, Austria, 2007.

[51] Côte, F., Abadie, C., Achard, R., **Cattan,** P., Chabrier, C., Dorel, M., De Lapeyre, L., Risède, J.M., Salmon, F., Tixier, P. (2007). How can pesticide use be reduced in banana culture? Approaches developed in the French West Indies: Integrated production system development and cropping system design using modelling. In: ProMusa Symposium: Recent advances in banana crop protection for sustainable production and improved livelihoods / ISHS, 2007/09/10-14, White River, South Africa. First ISHS. s.l.: s.n., 23 p. ISHS/ProMusa Symposium. 1, 2007-09-10/2007-09-14, White Rive, Afrique du Sud.

[52] Cabidoche, Y.-M., Clermont-Dauphin, C., Lafont, A., Sansoulet, J., **Cattan**, P., Achard, R., Caron, A., Chabrier. C. (2007). Devenir de pesticides organochlorés persistants dans les sols antillais : le cas de la chlordécone. Evaluation et réduction des risques liés à l'utilisation des pesticides. 7-9 nov 2007. Reims, France. Powerpoint

[53] Sansoulet, J., Cabidoche, Y.-M., **Cattan,** P., Ruy, S., Simunek, J. (2008). Modelling 3D spatially distributed water fluxes in an andisol under banana plants. In: IWRA. 13ème congrès mondial de l'eau, Montpellier, 1-4 septembre 2008. Montpellier : IWRA, 13 p. Congrès mondial de l'eau. 13, 2008-09-01/2008-09-04, Montpellier, France.

[54] Charlier, J. B., **Cattan**, P., Voltz, M., Moussa, R. (2009). Transport of a nematicide in surface and ground waters in a farmed tropical catchment with volcanic substratum In: Geophysical research abstracts. Vol 11, European Geosciences Union General Assembly. Vienne, Austria, 2009

[55] Bonin, M., **Cattan,** P. (2009). Dynamique des exploitations agricoles dans un contexte de crise. Le cas de la production bananière en Guadeloupe. In : Colloque International « Sociétés en transition et développement local en zones difficiles", 22-24 avril 2009, Djerba. s.l. : s.n., 13 p. Colloque International « Sociétés en transition et développement local en zones difficiles", 2009-04-22/2009-04-24, Djerba, Tunisie.

[56] Côte, F., Abadie, C., Achard, R., **Cattan,** P., Chabrier, C., Dorel, M., De Lapeyre, L., Risède, J.M., Salmon, F., Tixier, P. (2009.) Integrated pest management approaches developed in the French West Indies to reduce pesticide use in banana production systems. In: Jones David R. (ed.), Van den Bergh Inge (ed.). Proceedings of the international symposium on recent advances in banana crop protection for sustainable production and improved livelihoods, White River, South Africa, September 10-14, 2007. Louvain: ISHS [Belgique], p. 375-382. (Acta Horticulturae, 828). International Symposium on recent advances in banana crop protection for sustainable production and improved livelihoods. 1, 2007-09-10/2007-09-14, White River, Afrique du Sud.

[57] Le Bellec, F., **Cattan**, P., Bonin, M., Beauvois, C. (2009). Vers la construction de système de culture innovant : identification des contraintes liées au système de production grâce à une analyse des pratiques culturales chez les agrumiculteurs [Résumé]. In : Le Bellec Fabrice. Déphi projet. Journée Déphi Développement et évaluation des systèmes de productions horticoles intégrées en Guadeloupe : CIRAD Vieux-Habitants (Guadeloupe), 20 novembre 2008.

[58] Pak, L.T., **Cattan**, P., Colin, F., Voltz, M. (2009) Prédire la concentration en pesticides dans les eaux de rivière en zone volcanique tropicale humide. Journées d'Etude des Sols 10e édition du 11 au 15/05/02009, Strasbourg

[59] Cabidoche, Y.-M., **Cattan**, P., Clermont-Dauphin, C., Gaspard, S., Lesueur-Jannoyer, M., Merciris-Loranger, G. (2009) HCH et chlordécone (CLD) encore pour des siècles aux Antilles ? rencontre ADEME « Sites et sols pollués », Paris, 20-21 octobre 2009

[60] Lesueur Jannoyer, M., Achard, R., **Cattan**, P., Cabidoche, Y.-M. (2009). A decision tool to manage food safety and cropping systems: A study case of Chlordecone polluted fields in the FWI. 2nd Farming System Design Symposium, Session 2 Field scale farm design and improvement, Monterey USA, 23-26 august 2009.

[61] Germeau, M., Weynants, M., **Cattan**, P. Dorel, M. Javaux, M. (2010) Investigating hydropedological relations using quantified morphological data under banana plants on a transect in Guadeloupe. In: Geophysical research abstracts. Vol 12, European Geosciences Union General Assembly. Vienne, Austria, 2010.

[62] Pak, L.T., Voltz, M., Colin, F., **Cattan**, P. (2010) Modelling the contribution of groundwater flow to pesticide contamination of runoff water in a humid tropical catchment in the FrenchWest Indies In: Geophysical research abstracts. Vol 12, European Geosciences Union General Assembly. Vienne, Austria, 2010.

3.5 Rapports

[63] **Cattan** P. (2001). Rapport intermédiaire d'avancement du projet Gestion Des Transferts (eau, sol, produits phytosanitaires et engrais) à l'Echelle du Bassin Versant. 13p.

[64] **Cattan** P., Dulcire, M., Bonin M. (2003). Etude des risques de pollution d'origine agricole et Martinique et en Guadeloupe. Gestion des transferts (eau, sol, produits phytosanitaires et engrais) à l'échelle du bassin versant. Rapport final, CIRAD, Neufchâteau, Guadeloupe 59p.

[65] Findeling, A., **Cattan**, P., Chambarel, A. et al. (2005). Etude et modélisation à l'échelle locale des transferts 3D de l'eau de pluie concentrée par le bananier à la surface d'un andosol : rapport d'activité 2003-2005 du PN/ACI ECCO. Montpellier : CIRAD-CA, 2005. - 8 p., Français

[66] Cabidoche, Y.-M., Clermont-Dauphin, C., Lafont, A., Sansoulet, J., **Cattan**, P., Achard, R., Caron, A., Chabrier. C. (2006). Stockage dans les sols à charges variables et dissipation dans les eaux de zoocides organochlorés autrefois appliqués en bananeraies aux Antilles. Relation avec les systèmes de culture Rapport final d'exécution, mai 2006, 100p.

[67] Bonin, M., **Cattan**, P. (2007). Gestion des risques environnementaux liés à l'activité agricole en zone bananière Guadeloupéenne : référentiels environnementaux des principales cultures. Paris, CIRAD, 5-[40] p.

[68] **Cattan**, P., Jannoyer, M. (2007). B2C3I - Université Antilles Guyane. 2007. Pesticides aux Antilles. Réactualisation des besoins prioritaires de recherche. CIRAD, Neufchâteau, Guadeloupe 32p.

[69] **Cattan**, P., Bonin, M. (2008). Gestion des risques environnementaux liés à l'activité agricole en zone bananière Guadeloupéenne. Rapport final de projet, CIRAD, Neufchâteau, Guadeloupe 91p

[70] **Cattan**, P. (2009). Evaluation d'un système biobed pour le traitement des bouillies fongicides en sortie de hangar. Rapport de fin de projet. CIRAD, Montpellier, 12p.

3.6 Travaux encadrés ou coordonnés par l'auteur

3.6.1 Thèse

[71] Charlier, J.-B., 2007. Fonctionnement et modélisation hydrologique d'un petit bassin versant cultivé en milieu volcanique tropical. Thèse de Docteur de l'Université de Montpellier II Thesis, Montpellier, 247 pp

3.6.2 DEA, DAA, MASTER2

[72] Perpina, C. (2001) Spatialisation des propriétés hydrodynamiques du sol en relation avec les pratiques culturales et la toposéquence en zone bananière de Guadeloupe ; Diplôme de fin d'étude de l'INH Anger. 41p.

[73] Berger, A. (2002) Gestion de l'assolement dans les petites exploitations bananières de Guadeloupe (quelles alternatives à la monoculture bananière ?) Mémoire de fin d'étude pour l'obtention du DAA, ENSAM, Montpellier, 57p.

[74] Le Doze, S. (2004) Propositions pour l'élaboration d'un diagnostic agro-environnemental de bananeraies adapté à la zone de montagne de Capesterre-Belle-Eau (Guadeloupe). Diplôme d'ingénieur Agronome de l'INA PG. DEA Economie de l'Environnement et des ressources naturelles. INA Paris Grignon/ENGREF/Université de Paris X. 81p.

[75] Lazrak, El Guali (2005) Devenir du cadusafos sur des sols volcaniques de Guadeloupe sous culture bananière. Mémoire de DEA National de Science du Sol. Institut National Polytechnique de Lorraine 23p.

[76] Desbois, P. (2006) Analyse de la variabilité spatiale et temporelle du partage ruissellement - infiltration pour le système sol-bananier à la surface d'un andosol de Guadeloupe à l'échelle locale du bananier. Mémoire de DAA Génie de l'environnement, option eau. Agrocampus Rennes. 31p + annexes

[77] Stephan, X. (2006) Analyse des trajectoires d'évolution des exploitations bananières guadeloupéennes. Mémoire de Master 2 "Développement agricole et politique économiques dans les PED". Institut d'Etudes du Développement Economique et Social, Nogent sur Marne, France. 89p.

3.6.3 Autres

[78] Guinde, L. (1999), Culture bananière et environnement. Rapport de stage de 1ère année de Maîtrise de Sciences et Techniques, UAG Antilles Guyane. juillet 1999.

[79] Nouvelon, A. (1999). Redistribution de l’eau de pluie par le bananier : identification et quantification des principaux facteurs de variation. Rapport de stage CIRAD/INRA/ISTOM réalisé du 20 juin au 30 novembre 1999 65p.

[80] Amoravain, V. (2000). Analyse du système agraire sur un bassin versant bananier en Guadeloupe ; Diplôme de fin d’étude du CNEARC 88p.

[81] Gouyer, S. (2000). Evaluation du transport par ruissellement de surface sur andosol ; Diplôme de fin d’étude de l’ISTOM 55p.

[82] Champoiseau, A. (2001). Analyse des transferts d’eau en bananeraie : étude du partitionnement des eaux en ruissellement et en drainage pour deux systèmes de culture ; Diplôme de fin d’étude de l’ISTOM. 71p

[83] Labas, J. (2002) Evaluation des risques de ruissellement et d’érosion relatifs aux systèmes de culture à base de bananes en Guadeloupe ; Mémoire de fin d’étude de l’ISTOM 64p.

[84] Martin, J. (2004) Caractérisation expérimentale des transferts hydriques à la surface d'un andosol sous culture de bananier ; Mémoire de DESS Hydrogéologie et Environnement de la Faculté d’Avignon 54p.

[85] Cavasino, A. (2005) Caractérisation des propriétés hydrodynamiques des andosols sur un bassin versant cultivé en zone tropicale. Rapport de stage de 3e année de l'ISTOM, 70p.

[86] Félicité, O. (2006) Les transferts hydriques dans les andosols : Modélisation et élution de traceurs. Mémoire d'ingénieur de l'école Polytechnique d'Orléans.

[87] Feltz, N. (2008) Relations hydropédologiques au sein d’une séquence de sols dérivés de cendres volcaniques en Guadeloupe. Mémoire d’ingénieur de l’Université Catholique de Louvain 80p.

[88] Germeau, M. (2009) Etude des relations hydropédologiques au sein d’une topo-séquence de Guadeloupe. Mémoire d’ingénieur de l’Université Catholique de Louvain 92p.

Chapître 2. Synthèse des travaux scientifiques

1 Problématique générale

1.1 Parcours scientifique

1.1.1 1985-1990

J'ai débuté ma carrière à Kaolack au Sénégal (1985-1987) puis à Ouagadougou au Burkina Faso où j'ai résidé 11 ans (1987-1998). La problématique générale de recherche traitait de l'incidence des conditions de milieu soudano-sahéliennes, caractérisées par une forte compétition pour l'eau et les éléments minéraux, sur les relations entre les techniques culturales (notamment la fertilisation, les densités et les dates de semis) et la production de matière sèche. La plante étudiée était l'arachide qui représente une des principales sources oléagineuses dans ces zones. J'ai évalué les techniques culturales à travers la caractérisation des relations techniques/état du milieu/production sans faire appel à des déterminants aux niveaux supérieurs d'organisation de l'activité agricole (systèmes de culture, de production, agraires). Les méthodes employées étaient les enquêtes, qui ont permis d'explorer la variabilité pédoclimatique du milieu, complétées par des essais agronomiques multilocaux permettant de juger de l'effet d'une ou de quelques techniques en interaction. Au Sénégal, les résultats obtenus ont permis de redéfinir les normes de fertilisation pour l'arachide et d'identifier les techniques de culture ayant un impact majeur dans l'élaboration du rendement de l'arachide. Au Burkina, les résultats ont permis d'identifier les conditions techniques et pédoclimatiques permettant d'augmenter l'efficacité de phosphates naturels partiellement acidulés à faible solubilité. La limite de ces études résidait dans le fait que les relations (techniques+climat)/état du milieu/production décrites étaient insuffisamment explicitées d'un point de vue fonctionnel d'où la difficulté d'extrapoler les résultats en dehors des sites expérimentaux et le recours à un dispositif multilocal lourd et coûteux. Ce dernier constituait cependant un précieux outil de démonstration auprès des acteurs locaux, alors que les travaux s'inscrivaient fortement dans une problématique de développement local.

1.1.2 1991-1998

Ces années correspondent à une réorientation des activités vers des approches fonctionnelles. Le problème posé était celui du diagnostic de culture au champ, c'est-à-dire la recherche des causes du niveau de rendement obtenu. Il s'appuie sur le questionnement suivant : [1 LIMITATION] y a t-il eu limitation de la production ? [2 QUAND] Dans l'affirmative, quelles sont les périodes à l'origine de cette limitation, c'est à dire celles où la croissance et le développement des plantes ont-été perturbés ? [3 QUOI] Quelles conditions de milieu sont responsables de ces perturbations ? De là, il est possible de proposer des solutions de façon à lever les conditions limitantes identifiées si elles venaient à se reproduire. L'enjeu consiste alors à trouver un certain nombre d'indicateurs, observables à la récolte, et témoignant des différents stress subis au cours de la culture.

Parmi ces indicateurs, le rendement en organes récoltés (grains, gousses…) a longtemps été la variable privilégiée pour révéler l'existence d'un « problème » au cours de la culture. Sa valeur diagnostique reste cependant faible : le niveau de rendement nous renseigne sur la marge de progression mais ne nous dit pas quoi faire pour progresser. C'est en effet une variable agrégative qui reflète l'ensemble des conditions de milieu auxquelles la plante à été soumise durant sa croissance et son développement. Aucune information n'est donnée tant sur les phases du cycle où la croissance ou le développement ont été limités que sur les conditions de milieu à l'origine de cette limitation ; d'où la difficulté de proposer des améliorations techniques efficientes. Ceci est d'autant plus vrai dans le cas plus spécifique des agricultures du sud. En effet les conditions de milieu y sont peu favorables à la culture et les niveaux d'intensification sont faibles. Il en résulte une multiplicité de facteurs limitants qui entraîne une large variabilité de réponse aux techniques (labour, fertilisation…) et une difficulté de diagnostic.

Pour pallier ces inconvénients, une méthode diagnostique a été développée en France métropolitaine dans les années 1980 en se basant sur l'observation de composantes du rendement formées à des périodes distinctes du cycle (Carrouee et al., 1989; Durr, 1984; Duthion et al., 1988; Fleury et al., 1994; Fleury et al., 1982; Jeuffroy, 1987; Leterme, 1988; Meynard and David, 1992; Munier-Jolain, 1994; Ney et al., 1994; Pigeaire et al., 1988; Sebillotte, 1987; Turc, 1988). Ainsi, le niveau de chaque composante constitue alors un indicateur des conditions de milieu au moment de sa formation. Par exemple chez le maïs, un faible nombre de pieds - *une des 3 composantes du rendement pour cette plante qui sont le nombre de pieds par m², le nombre de grains par pied et le poids moyen d'un grain qui s'élaborent à des périodes différentes* - renvoie à des problèmes au cours de la germination ; un faible nombre de grains renvoie à des contraintes de croissance et développement au moment de l'épiaison... Cependant, si chez les plantes à croissance déterminée comme le maïs les phases d'élaboration des composantes sont le plus souvent disjointes, le cas des plantes à croissance indéterminée est plus complexe en raison du chevauchement des phases (mise en place des graines alors que la croissance végétative n'est pas terminée par exemple). L'établissement de la chronologie de mise en place des organes reproducteurs et la caractérisation des synchronismes de développement sur les différents rameaux des plantes permet cependant de décrire de façon synthétique la mise en place du nombre de graines et de leur poids sur la plante. La caractérisation de l'effet de diverses contraintes de croissance (stress hydrique, ombrage …) sur l'allocation des assimilats entre parties végétative et reproductrice au cours du cycle et sur les composantes du rendement permet finalement d'identifier un certain nombre de variables (rapport partie végétative / partie reproductrice, nombre de graines…) observables à la récolte et utilisées pour porter un diagnostic à postériori. Le pois et le soja ont principalement fait l'objet de tels travaux en métropole. En milieu tropical, la mise en œuvre de cette méthode d'analyse pour des plantes à croissance indéterminée telles l'arachide et le sésame était inédite.

C'est ainsi que j'ai conduit une thèse sur la thématique de l'élaboration du rendement de l'arachide (1993-1996), approche nouvelle pour cette plante tropicale à croissance indéterminée, dans le but d'apprécier l'effet des techniques et des états du milieu sur le rendement, et de développer des méthodes de diagnostic au champ. Les résultats obtenus ont permis de préciser la chronologie de mise en place des organes reproducteurs de l'arachide en relation avec la croissance (Cattan and Fleury, 1998). Une méthode d'analyse du rendement a également été proposée (Cattan, 1994; Cattan, 1996). Parallèlement à ces travaux, un travail de base sur la formalisation des relations entre croissance et rayonnement a été entrepris pour l'arachide, dans une optique de modélisation de la croissance de la plante. Trois années de résultats ont permis d'édifier les bases d'un modèle simple d'élaboration de la matière sèche. Ces études ont trouvé en partie leur application dans la caractérisation de variétés d'arachide ayant diverses longueurs de cycle, et ont permis d'expliquer les écarts de production obtenus en réponse à des stress de croissance intervenant à différents moments du cycle. Ils ont également participé à définir des idéotypes pour l'amélioration variétale, basés notamment sur la durée souhaitable des différentes phases du cycle en fonction de leur sensibilité à la sécheresse. Pour le sésame des travaux similaires ont permis de lever une part des interrogations portant sur l'incapacité de la plante à assurer des rendements élevés. Il a été proposé de faire porter les efforts de sélection sur la longueur de la période de remplissage des fruits ainsi que sur l'amélioration du rendement au décorticage des capsules alors que l'efficience de transformation de l'énergie radiative en biomasse et le taux d'allocation des assimilats à la partie reproductrice étaient dans les normes et ne laissaient pas entrevoir de possibilité d'amélioration.

1.1.3 1999-2008

J'ai rejoint le CIRAD FLHOR en Guadeloupe en janvier 1999. Cette mobilité administrative et géographique s'est accompagnée d'une évolution thématique passant de l'agrophysiologie aux processus hydrologiques et aux transferts de polluants, ce qu'autorisait ma formation initiale en science du sol. Bien qu'il existât un enjeu fort sur la compréhension de l'élaboration du rendement de la banane pouvant déboucher sur une meilleure gestion des plantations, cette évolution thématique vers l'hydrologie et les transferts fut justifiée par un contexte de forte demande sociétale sur l'évaluation de l'impact environnemental des cultures bananières. De par ma double formation, c'est à travers le développement de la plante et de son architecture que les transferts de polluants on été abordés. Deux questions de fond ont guidé les travaux et ont porté : 1) sur le devenir des pesticides épandus en parcelle 2) sur les moyens de réduire les impacts environnementaux des pratiques agricoles.

Outre l'investissement scientifique, le traitement de ces questions a nécessité un fort investissement dans la recherche de partenaires scientifiques et financiers concrétisés au sein de divers projets (10 projets échus dont 4 en tant que coordonnateur). Des résultats originaux, portant sur l'analyse spatiale des processus et leur modélisation, mais aussi sur les exploitations agricoles et les déterminants des pratiques, ont été obtenus et publiés. Ils constituent une base pour l'évaluation de l'effet des pratiques agricoles sur l'environnement.

Les résultats obtenus ont notamment permis de répondre à de nouveaux défis. Ainsi, l'investissement récent (2008) des services de l'état sur la problématique de la Chlordécone, un insecticide organochlorés épandus en bananeraie jusqu'en 1993, s'est traduit par un investissement particulier sur ce thème. Dans ce cadre j'ai pris en 2008 la coordination d'une réponse à l'appel à projet CES de l'ANR avec un partenariat s'appuyant d'une part sur les connaissances approfondies du milieu et de son fonctionnement capitalisées localement par l'INRA (UR APC), l'UAG (laboratoire de biologie marine) et le CIRAD (UR Systèmes Banane et Ananas) et d'autre part sur des techniques d'investigation de pointe (éléments marqués, RMN…) développées par les laboratoires spécialisés de Montpellier (UMR LISAH), Rennes (UMR Ecologie et Sante des Ecosystèmes), Toulouse (UMR Xénobiotiques) et Jülich (Agrosphere Institute). Le projet CHLORDEXCO a ainsi été déposé et accepté en juillet 2008. Parallèlement, l'investissement s'est poursuivi sur la thématique de l'évaluation des impacts environnementaux des cultures à partir de modèles biophysiques et s'est traduit par l'acceptation d'un sujet de thèse sur un cofinancement CIRAD / SupAgro (Montpellier).

1.1.4 Conclusion

Ainsi, mon parcours m'a permis, au travers de contextes géographiques différents (Sénégal, Burkina Faso, Guadeloupe) et de mon évolution thématique, d'apprécier la complexité des phénomènes mis en œuvre dans le processus de production agricole. La principale conséquence a été d'une part d'inscrire les activités de recherche au sein de projets pluridisciplinaires, à même de répondre à cette complexité et notamment mêlant processus biophysiques et socio-économiques, et d'autre part de pouvoir resituer les résultats dans un contexte global. Ceci m'a permis de développer des actions larges dans le domaine relatif aux impacts environnementaux des cultures. Dans le cadre de cette HDR je présenterai plus particulièrement les travaux engagés sur les processus hydrologiques associés aux transferts de polluants aux différentes échelles de l'espace agricole, travaux sur lesquels je me suis particulièrement investi ces dernières années.

1.2 Situation générale du programme de recherches

1.2.1 Contexte

Le contexte dans lequel se sont inscrites mes activités des dernières années est celui des systèmes de culture intensifs à base de bananiers et à hauts niveaux d'intrants en zone volcanique tropicale. L'utilisation massive en bananeraie de pesticides organochlorés (Chlordécone notamment) jusque dans les années 90 est à l'origine de pollutions avérées des sols, des ressources en eau et des organismes vivants. Les conséquences actuelles s'évaluent à plusieurs niveaux : contamination durable des sols sans possibilité facile de remédiation ; arrêt de la culture des tubercules en zone contaminée obligeant à des réorientations culturales ; suspicion générale sur les produits de l'agriculture antillaise ; remise en cause et inquiétude vis à vis des conditions de productions actuelles faisant appel à d'autres familles de molécules (organophosphorés notamment)…

De façon générale, la méconnaissance par les praticiens des principaux mécanismes contrôlant le devenir des pesticides épandus en milieu tropical est en partie à l'origine des problèmes environnementaux que connaissent les Antilles, et les zones bananières du monde plus généralement (Bonan and Prime, 2001; Castillo et al., 2000; Diaz Diaz et al., 1998; Henriques et al., 1997; McDonald et al., 1999; Rawlins et al., 1998). Les références expérimentales sont très réduites notamment au plan des processus de dispersion des matières actives utilisées sur cultures tropicales. Ainsi, il est difficile de formuler des recommandations spécifiques pour améliorer l'évaluation ex ante de l'impact de l'utilisation de nouvelles molécules en milieux et cultures tropicaux lors des procédures d'homologation. Ensuite, pour les usages déjà homologués et à l'origine de contaminations avérées ou suspectées, l'insuffisance de connaissances ne permet pas, d'une part, de définir des indicateurs fiables permettant l'évaluation objective de l'étendue des contaminations et des risques d'impacts et, d'autre part, la proposition de solutions permettant de limiter l'étendue des contaminations : par exemple modalités d'apport en parcelle (dates, fréquences, zones d'épandage…) ; implantation de couvertures végétales modifiant le partage ruissellement infiltration ou pouvant favoriser la rétention et la dégradation des molécules.

De nombreux travaux traitent des processus à l'origine de la dispersion des pesticides dans l'environnement (Aubertot et al., 2005; Calvet, 2005; Cheng, 1990; Voltz and Louchart, 2001) et de leur impact environnemental. Ils se rapportent généralement : à la caractérisation de la rétention des molécules dans les sols, via la détermination d'isothermes d'adsorption et de désorption menées en conditions contrôlées et aboutissant à la détermination du coefficient Kd ou Koc (revue de (Wauchope et al., 2002; Weber et al., 2004) ; à l'analyse de la dégradation biotique des molécules dans les sols et des facteurs environnementaux susceptibles de l'influencer (Houot et al., 2000) ; à l'étude des processus de mobilisation et de transport par les flux de ruissellement et de percolation en surface et au sein du profil de sol (Beck et al., 1996; Calvet, 2005; Elliott et al., 2000; Louchart et al., 2001) ; à la compréhension de l'intégration des processus de rétention et de transport à l'échelle des hydrosystèmes (relation nappes / eaux de surface / zone littorale). Les références acquises sur ces sujets l'ont été majoritairement en milieux tempérés. Elles sont encore très partielles comme le montre l'expertise collective INRA/Cemagref (Aubertot et al., 2005), commanditée par le MEDD et le MAP en 2005. Elles ne sont, de surcroît, pas directement transposables aux milieux tropicaux du fait de spécificités fortes de ces derniers.

1.2.2 Spécificités du milieu : climat tropical et volcanisme

Aux Antilles, climat et volcanisme sont à l'origine de conditions de milieu particulières qui vont influer sur le devenir des pesticides.

En premier lieu climat et volcanisme ont induit une forte variabilité spatiale des types de sol sur de très courtes distances. En effet, le climat, chaud et humide, est un des principaux moteurs de différenciation des types de sols sur un matériau volcanique jeune, bien drainé (Ndayiragije, 1996). Dans ces zones à fort relief, les variations d'altitude ont induit une forte variation des conditions climatiques et de là des types de sol. Deux grands types de sol sont ainsi rencontrés et ont comme principal point commun une forte capacité d'infiltration (conductivité hydraulique à saturation supérieure à 60 mm h^{-1}). Aux basses Altitudes (<100m), la pluviométrie plus faible que l'évapotranspiration et l'ensoleillement important ont induit des périodes de dessèchement temporaire du sol favorisant la formation d'halloysite et ont conduit à des Nitisols. En altitude (>150m), les conditions plus pluvieuses ont conduit à la genèse d'Andosols caractérisés par la présence de minéraux amorphes (c'est-à-dire non cristallisés). Ces amorphes possèdent une très forte réactivité en raison de leur surface spécifique considérable (jusqu'à 1000 m^2/g) ; ils présentent un effet protecteur vis-à-vis de la matière organique avec laquelle ils s'associent pour former des complexes organo-minéraux (Legros, 2007). Ces sols sont naturellement très riches en hydroxyles et en matières organiques, ce qui leur confère des charges variables selon le pH, et la capacité de fixer cations et anions. Une autre particularité des Andosols tient à la structure des agrégats allophaniques : forte teneur en eau, faible densité et structure fractale (Woignier et al., 2007; Woignier et al., 2006) associée à une faible perméabilité microscopique. Les propriétés des agrégats allophaniques sont ainsi susceptibles de réduire la mobilité des molécules ce qui peut contribuer à expliquer leur séquestration. Finalement, les caractéristiques particulières d'échange et de structure des Andosols, ajoutées aux forts taux de matière organique rencontrés (plus de 15% contre environ 2% pour les Nitisols), font que ces sols sont susceptibles de retenir fortement les molécules, dont les pesticides épandus dans le cadre des activités agricoles.

En second lieu l'importance des précipitations est à l'origine d'une circulation intense des eaux qui va essentiellement emprunter des voies souterraines en relation avec la forte infiltration des sols. Ces écoulements s'opèrent dans un milieu souterrain complexe qui résulte de la succession de projections hétérogènes structurant les circulations d'eau souterraines ainsi que l'individualisation d'aquifères.

Pour résumer, ce contexte de sol infiltrant a été peu étudié dans le cadre des pollutions agricoles, alors que l'étude du transport par ruissellement a été le plus souvent privilégié (Lennartz et al., 1997; Leonard, 1990; Leu et al., 2004; Louchart et al., 2001). De plus, Andosols et Nitisols, ont été peu étudiés vis à vis des processus de rétention et contamination par les pesticides. L'existence de cultures intensives à hauts niveaux d'intrants telle la banane a justifié qu'on s'intéresse activement à caractériser le devenir des pesticides dans ce contexte pédologique et climatique particulier.

1.2.3 Le système de culture comme outil de gestion du milieu

Dans les travaux traitant des processus à l'origine de la dispersion des pesticides, l'influence des pratiques agricoles, ou plus généralement de la mise en culture du milieu, sur ces processus n'est le plus souvent pas explicitement abordée. De fait les recommandations pour maîtriser les pollutions portent essentiellement sur le choix et la manière d'employer les produits polluants ainsi que sur les aménagements du paysage (bandes enherbées par exemple - (CORPEN, 1997) plutôt que sur le changement des itinéraires techniques en parcelle pour influer sur l'un ou l'autre des processus déterminant la dispersion des polluants. Or les pratiques agricoles modifient profondément les propriétés du sol et les conditions de transfert. Par exemple, de nombreux auteurs notent l'incidence des pratiques culturales sur les caractéristiques hydrodynamiques de la surface du sol (infiltrabilité) ainsi que sur son modelé (rugosité, détention superficielle) et par là même sur le ruissellement (Vensteelant et al., 1997) : diminution de l'infiltration sur les traces de roues (Basher and Ross, 2001; Hill, 1993) ; augmentation de l'infiltration immédiatement après travail du sol (Rao et al., 1998a; Rao et al., 1998b) ; création de zones préférentielles de circulation et de concentration des eaux par les opérations culturales (Takken et al., 2001a). Il en est également ainsi du labour (ou de l'emploi du pulvériseur à disque fréquemment utilisé aux Antilles), affectant la macroporosité des horizons de surface (Dorel, 1993). D'autre part les propriétés d'adsorption des sols peuvent également être modifiées. Par exemple, la dépendance des capacités d'échange anionique et cationique en fonction du pH pour les Andosols fait que les propriétés d'adsorption sont susceptibles d'être affectées par des pratiques comme le chaulage. Les capacités d'échange du sol sont également dépendantes du taux de matière organique du sol qui peut être soit augmenté par des apports soit réduit sous l'effet du travail du sol comme Clermont Dauphin et al. (Clermont Dauphin et al., 2004) l'observent dans les exploitations agricoles de Guadeloupe. Enfin les éléments adsorbés sur le sol sont susceptibles d'être déplacés par différents ions, notamment ceux utilisés pour la fertilisation. Dans le cas des Antilles, Clermont Dauphin (Clermont Dauphin et al., 2004) note ainsi la baisse du stock de calcium par une fertilisation en excès de potassium dans les sols à halloysite.

De là, notre démarche emprunte le point de vue de l'agronome : le système de culture comme outil de gestion du milieu agricole. Il s'agit moins ici d'étudier un processus que de déterminer comment un système de culture peut affecter chacun des processus intervenant dans la dispersion des polluants et quelles en sont les conséquences aux différentes échelles de l'espace agricole. Cette démarche est à même d'une part d'évaluer la responsabilité des pratiques agricoles sur les pollutions, et, d'autre part, de préciser le champ des actions possibles pour les agriculteurs permettant de limiter les impacts environnementaux. Le cas de la banane a été choisi en raison de son importance (environ 1,6 M d'ha dans le monde dont 0,4 en banane export, avec des implantations sur sols volcaniques dans la Caraïbe, l'Amérique Centrale, et quelques parties d'Afrique) et des hauts niveaux d'intrants qu'elle requiert, donc d'atteintes prévisibles à l'environnement.

1.2.4 Conclusion

Ce recueil de travaux destiné à l'obtention du diplôme d'habilitation à diriger des recherches traite donc de l'influence des systèmes de culture bananiers sur les processus déterminant la dispersion des pesticides utilisés en bananeraie et des conséquences sur la pollution des ressources en eau aux différentes échelles de l'espace agricole dans le contexte d'un milieu volcanique tropical humide. Ces recherches sont intimement liées à l'étude des processus hydrologiques qui tiennent une place prépondérante dans les processus de dispersion. Les autres voies de dispersion, volatilisation notamment, n'ont pas été abordées. Ces recherches ont été menées dans un but prédictif et en vue de tester différents scénarios de gestion de l'espace. Elles se sont appuyées sur des modèles qu'elles ont alimentés, conférant par là même une généricité aux résultats obtenus. Elles reposent sur une base expérimentale forte à différentes échelles qui a permis d'une part d'identifier et quantifier les processus et d'autre part de valider les modèles utilisés. Cette base expérimentale constitue un socle de connaissance pour d'autres partenaires.

Ces recherches sont parties d'un simple (sinon simpliste) constat, issu de ma rencontre avec François Bussière de l'INRA en Guadeloupe : *la quantité d'eau arrivant au pied du bananier est beaucoup plus importante que celle arrivant dans l'interrang*. Au cours de ce recueil, on verra en quoi ce phénomène est susceptible d'avoir des répercutions sur les écoulements jusqu'à l'échelle du bassin versant. Mes recherches ont été conduites en 2 phases.

- ⇨ La première s'est intéressée à comprendre comment les pesticides étaient mobilisés à partir de leur lieu d'épandage, c'est-à-dire la parcelle. Je me suis ainsi attaché à déterminer comment la culture de bananier modifiait les flux hydriques en ruissellement et drainage ainsi que le transport de pesticide associé. Ces travaux ont permis d'identifier les variables de base pour la caractérisation des écoulements en parcelle et destinées à être intégrées dans des modèles de simulation des flux hydriques.

⇨ La seconde s'est intéressée aux mécanismes de pollution de la ressource en eau à l'échelle du bassin versant. Une double approche expérimentale et de modélisation a été entreprise. L'approche expérimentale a permis de caractériser les grands flux hydriques au sein d'un petit bassin d'altitude majoritairement planté en banane ainsi que d'y dresser les premières hypothèses en matière de transport de polluant. L'approche de modélisation a débouché sur un modèle spatialisé autorisant l'évaluation de l'effet des systèmes de culture bananiers sur les écoulements.

L'objectif ambitieux de traiter des processus hydrologiques à différentes échelles et de les modéliser, n'a pu être réalisé qu'avec les collaborations soutenues avec l'Unité Agropédoclimatique de la Zone Caraïbe (APC) de l'INRA en Guadeloupe (Y.-M. Cabidoche et F. Bussière) et de l'UMR LISAH à Montpellier (M. Voltz, R. Moussa, C. Saison, X. Louchart et tout récemment F. Colin) sans lesquels ces recherches n'auraient pu ni voir le jour et ni aboutir. Il n'a également été possible que grâce à la contribution des étudiants, appuyés par une équipe technique dévouée (Germain Onapin et Colbert Behary), et surtout de la thèse de J.B. Charlier, que j'ai pu encadrer. Leur motivation et leur investissement ont été déterminants dans la réussite de ces travaux. Il n'a enfin été possible que grâce aux financements acquis par l'intermédiaire de différents projets que j'ai montés ou auxquels j'ai participé (voir CV) et notamment grâce au soutien financier de la DIREN de Guadeloupe, de la Région Guadeloupe et de l'Europe.

2 Transport et dispersion des pesticides à l'échelle parcellaire

Si le bananier est une herbe géante, une bananeraie ne possède cependant pas le statut d'une parcelle de blé. En effet, les interventions culturales des grandes cultures se raisonnent à l'échelle de la parcelle. Mais, dans la cas de la banane, notamment en raison de la non mécanisation des interventions agricoles au champ, l'agriculteur raisonne et spatialise la plupart de ses pratiques en fonction de l'implantation des bananiers sur la parcelle : application des nématicides ou insecticides, voir des engrais à proximité des pseudo-troncs ; tracé de sillons de plantations pour les bananiers ; restitution des feuilles sur tous les interrangs ou un interrang sur deux en cours de culture ; irrigation au goutte à goutte au pied de chaque plant… L'échelle d'étude agronomique qui a pour vocation de traiter des pratiques se doit de considérer la même échelle c'est-à-dire celle de la plante. Différents travaux avaient noté l'extrême variabilité des conditions de milieu en bananeraie (Dorel, 1991; Dorel, 1993) et l'incidence sur les transferts (Khamsouk, 2000) et ont révélé de fait l'insuffisance de l'échelle parcelle pour rendre compte des transferts. Ce changement d'échelle de perception et d'étude constitue la caractéristique majeure des travaux engagés en parcelle.

A mon arrivée en Guadeloupe, le problème de la dispersion des pesticides avait commencé à être abordé dans le cadre d'une expérimentation destinée à mesurer globalement à l'échelle de la parcelle les quantités de trois nématicides transportées par les eaux de ruissellement (Dorel et al., 1996). D'autre part un bilan des exportations d'éléments solubles avait été approché en Martinique en mesurant les flux de ruissellement et de percolation sous bananiers (Khamsouk, 2000). L'absence de prise en compte de l'ensemble des écoulements (notamment drainage dans le cas de l'étude sur les nématicides) et de leur variabilité spatiale (pas de mesure des flux dans l'interrang en Martinique), n'a pas permis de correctement quantifier les exportations et de dresser des bilans. Mon premier travail fut d'améliorer ces dispositifs de façon à mesurer l'ensemble des écoulements (ruissellement mais aussi drainage), à prendre en compte l'ensemble de la variabilité intraparcellaire (échantillonnage sous le bananier mais aussi entre les bananiers), et enfin à disposer d'un pas de temps de mesure permettant de mettre en évidence des dynamiques de flux plutôt que des quantités totales écoulées. Deux principaux dispositifs expérimentaux ont servi de support aux études qui se sont déroulées entre 2001 et 2006. Le premier à l'échelle de la parcelle, permettait de comparer les flux de ruissellement à l'exutoire de deux parcelles de 3000 m² afin de tester différents systèmes de culture. Ce dispositif perdure depuis sa date d'implantation en 2001 et a servi de support aux études sur le ruissellement, le drainage et le comportement des pesticides en parcelle. Le second dispositif est à l'échelle d'un bananier et est inclus dans l'une des deux parcelles du dispositif principal. Il s'agit d'une placette de 8m² équipée en 2004 et permettant de mesurer à cette échelle élémentaire l'ensemble des flux en ruissellement et en drainage ainsi que les changements d'état du milieu correspondant (potentiel de l'eau du sol, humidité). Ces dispositifs sont décrits dans différentes publications et rapports cités ci-après.

2.1 Fonctionnement hydrologique de la bananeraie

En bananeraie, la simple observation des écoulements au cours d'un épisode pluvieux montre que la quantité d'eau arrivant au pied du bananier est beaucoup plus importante que celle arrivant dans l'interrang. De nombreux travaux montrent que la mise en culture modifie en premier lieu la répartition de la pluie au sol du fait de l'interception par les couverts végétaux (Levia Jr. and Frost, 2003; Llorens and Domingo, 2007). Cette redistribution de la pluie au sol interagit avec les pratiques en parcelle pour influer sur les écoulements d'eau. Trois questions se posaient alors : quel est l'effet du couvert (1) sur la redistribution de la pluie au sol, (2) sur le ruissellement et (3) sur le drainage.

2.1.1 La redistribution de la pluie par le couvert

Différents auteurs constatent que l'interception de la pluie par les plantes conduit à des écoulements préférentiels à travers le couvert végétal (Herwitz, 1993; Navàr, 1993). Le tronc constitue dans la plupart des cas, la principale voie d'écoulement de la pluie interceptée par le couvert vers le sol : ce type d'écoulement est appelé stemflow. Une autre partie de la pluie incidente s'écoule à travers le couvert (throughfall) de façon hétérogène, les zones d'égouttage succédant aux zones protégées. Ces phénomènes conduisent à une forte variabilité spatiale des intensités de la pluie transmise au sol. La répartition entre stemflow et throughfall dépend de la structure de la plante (Crockford and Richardson, 2000; Manfroi et al., 2004) ainsi que des conditions climatiques au cours de la pluie (Levia, 2004). La plupart des travaux ont porté sur les forêts, les cultures étant peu étudiées. Une seule référence existait sur plantain (Jimenez and Lhomme, 1994) et signalait un fort stemflow.

Figure 1 : Dispositif de mesure de la redistribution de la pluie par le feuillage en bananeraie

Les travaux ont été menés en 1999 dans le cadre du projet BANENVI (voir CV) avec F. Bussière de l'APC de Guadeloupe qui avait déjà abordé les questions de redistribution de la pluie sur maïs. Nos travaux on consisté à caractériser l'interception de la pluie dans une bananeraie et à quantifier les flux et leur hétérogénéité à la surface de sol. L'influence du stade de développement de la culture a plus particulièrement été étudiée en retenant des paramètres de surface foliaire et de forme de feuilles (Cattan et al., 2007a). Le dispositif expérimental était constitué de 3 parcelles d'âge différent. Le stemflow était mesuré grâce à un dispositif de cerclage du tronc permettant de récolter l'eau s'écoulant par cette voie ; la répartition des intensités au sol était approchée par des collecteurs de 0.05 m² disposés au sol (Figure 1).

Les résultats ont montré un stemflow considérable, proportionnel à la surface foliaire du bananier et représentant 18 à 26% du volume de pluie incident suivant l'âge de la culture. Considérant que ce volume de pluie arrive sur une surface réduite correspondant aux pieds des bananiers qui occupent moins de 1% de la surface totale, l'intensité pluviométrique s'y trouve multipliée par un coefficient de 28 par rapport à la pluie incidente. Sous le couvert, l'intensité moyenne décroit quand l'indice foliaire augmente. L'hétérogénéité spatiale est cependant forte et des intensités localement 5 fois plus fortes que la pluie incidente sont enregistrées. La répartition spatiale des intensités n'est pas aléatoire et dépend de la distance par rapport au pseudo-tronc du bananier : avant la jetée du régime, la zone à proximité du pseudo-tronc apparaît protégée de la pluie incidente.

Ces travaux ont révélé l'importance de l'hétérogénéité des flux incidents intraparcellaires. Ils ont connu par ailleurs un développement générique en modélisation qui a été conduit par l'INRA APC en Guadeloupe (modèle DROP, (Bussière et al., 2002) permettant de simuler la répartition de la pluie sous couvert. Pour nos études, ils ont été essentiels dans la compréhension du fonctionnement hydrologique de la bananeraie, déterminant les conditions aux limites locales. Leur incidence dans les processus de ruissellement et de drainage dans le sol est exposée ci-après.

Principales publications ou communications relatives au thème

- ↳ **Cattan**, P., Bussière, F., Nouvellon, A., (2007) Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation. Hydrological Processes. Vol 21, p 2196-2205
- ↳ Cabidoche, Y.-M., **Cattan**, P. (2004). Fonctionnement hydrologique distributif du système bananier - andosol cultivé. Conséquences sur les stockages et flux d'intrants solubles localisés : Fonds commun INRA/CIRAD année 2000 - Projet n°28. In : Séminaire de restitution. Appels à proposition 2000 et 2001 du fonds commun Inra-Cirad, Montpellier 7 et 8 septembre 2004. - Montpellier : CIRAD p. 14-15 , Français.

2.1.2 L'impact du couvert et des pratiques d'entretien du sol sur le ruissellement

Le ruissellement est un des principaux agents de pollution des eaux dans les zones agricoles (Leonard, 1990). Le processus d'apparition du ruissellement en bananeraie devait être décrit. Fondamentalement, le ruissellement est la part de l'eau de pluie incidente qui ne s'infiltre pas et qui est redistribuée spatialement selon le modelé de surface. Les facteurs contrôlant l'infiltration sont nombreux. Ils ont trait à l'état hydrique du sol, à ses propriétés hydrodynamiques, et aux conditions aux limites. Ils sont distribués de façon hétérogène en parcelle. La production de ruissellement sera donc hétérogène et l'on distingue des surfaces contributives au ruissellement (c'est-à-dire qui ruissellent) et d'autres non contributives où toute l'eau s'infiltre. Si les surfaces contributives sont connectées, l'eau sera acheminée en dehors de la parcelle vers le réseau hydrographique. Ainsi, le ruissellement apparaît déterminé par les surfaces ayant les conditions d'infiltration les plus défavorables ; une conséquence est qu'il est possible d'observer du ruissellement pour des intensités pluviométriques moyennes inférieures à la capacité d'infiltration moyenne d'une parcelle (Hawkins, 1982; Morin and Kosovsky, 1995), paramètre habituellement mesuré. De nombreux travaux ont montré l'incidence des états de surface en parcelle sur le déclenchement du ruissellement (Bromley et al., 1997; Casenave, 1991; Leonard et al., 2006; Richard et al., 1999; Rockström et al., 1998). L'influence des pratiques culturales est connue pour affecter localement les propriétés hydrodynamiques des sols (tassement dû au passage d'outil ou des ouvriers, augmentation de la porosité par le travail du sol…). En revanche peu de travaux ont pris en compte les variations des intensités pluviométriques au sol du fait de la redistribution par le couvert végétal pour expliquer le ruissellement.

Ces études ont été abordées dans le cadre des projets DIREN1 et PNRH (voir CV) et ont été conduites en partenariat avec les équipes de l'UMR LISAH de Montpellier et de l'INRA Guadeloupe ainsi que de l'INRA d'Avignon et du CIRAD Montpellier (UPR Recyclage et Risque). Les travaux ont été conduits à l'échelle parcellaire de 2001 à 2002 ainsi qu'à celle du bananier de 2004 à 2005. A l'échelle du bananier les mesures physiques d'écoulement et de variables d'état du milieu ont été complétées par une acquisition vidéo permettant d'observer le phénomène de ruissellement.

Figure 2 : le ruissellement se propage à partir du pseudo-tronc du bananier

A l'échelle de la plante, les résultats (Cattan et al., 2009) confirment que le stemflow et les zones d'égouttage induisent du ruissellement. Notamment, les relevés tensiométriques au cours des événements pluvieux ont montré une augmentation des potentiels en aval du pseudo-tronc de bananier, délimitant une zone de propagation du ruissellement observé sur les images vidéo (Figure 2). Un autre résultat important concerne le caractère hortonien du ruissellement, c'est-à-dire par dépassement de la capacité d'infiltration du sol. L'hypothèse d'une saturation de l'ensemble du profil ou des horizons superficiels a été rejetée au vu de l'observation des relevés tensiométriques. Une modélisation simple a été développée (Cattan et al., 2009) permettant d'évaluer l'influence du stemflow sur le phénomène de ruissellement. Le modèle considère deux unités hydrologiques dans lesquelles les intensités pluviométriques ainsi que les capacités d'infiltration peuvent varier. Le volume de ruissellement est la somme des différences positives entre pluie et infiltration à chaque pas de temps. Les simulations montrent que le stemflow ne peut seul contribuer au déclenchement du ruissellement en parcelle. Il est notamment nécessaire de tenir compte de la variabilité spatiale des capacités d'infiltration selon les états de surface qui reste le principal facteur explicatif du volume ruisselé. Les simulations ainsi que l'analyse des résultats aboutissent à retenir une capacité d'infiltration dans les zones contributives au ruissellement bien inférieure à la conductivité hydraulique à saturation moyenne mesurée sur les parcelles (moins de 10 mm h^{-1} contre près de 70 mm h^{-1} en moyenne mesurés). La recherche d'une cohérence entre valeurs mesurées et simulées suggère une réduction des capacités d'infiltration dans les zones contributives au ruissellement au cours d'un épisode pluvieux. Des recherches doivent être entreprises pour expliquer l'origine de cette réduction.

Du fait de la connectivité des zones contributives au ruissellement, les résultats ci-dessus ont un impact à l'échelle de la parcelle. Ainsi, le ruissellement a été observé en parcelle pour des intensités pluviométriques inférieures aux valeurs mesurées des conductivités hydrauliques à saturation (Cattan et al., 2006). En plus de l'effet « stemflow », une forte variabilité des propriétés hydrodynamiques des sols était observée soit spatiale (tassements dus aux passages de roues, meilleure infiltration dans les parties travaillées) soit temporelle avec une réduction des conductivités hydrauliques au cours du temps (tassement de la zone travaillée du profil). L'effet « stemflow » sur le ruissellement a indirectement été confirmé en empruntant les voies de la modélisation (Charlier et al., 2009b). Comme à l'échelle du bananier, un modèle à deux compartiments a été utilisé : un compartiment dans lequel se déverse le stemflow, l'autre compartiment étant représentatif uniquement des écoulements sous couvert. Les simulations d'hydrogrammes montrent que la prise en compte de l'effet « stemflow » améliore la simulation du ruissellement, notamment en fin de crue.

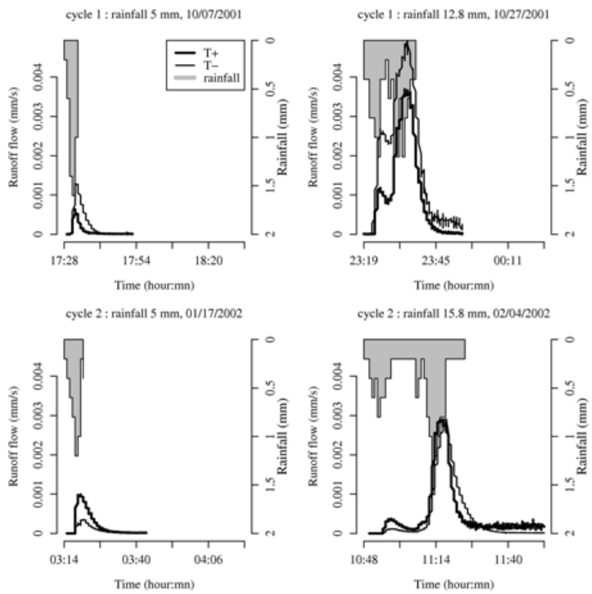

Figure 3 : hydrogramme de ruissellement en parcelle travaillée (T+) et non travaillée (T-) selon le cycle de culture et le volume pluviométrique

Quoiqu'il en soit, seule une faible partie des pluies (15%) occasionne du ruissellement sur le long terme (près d'une année de mesure à cheval sur deux cycles culturaux), étant donné la distribution des intensités pluviométriques dans la zone étudiée. Les coefficients de ruissellement restent faibles (5 à 11%) et n'excèdent pas 34% à l'échelle de l'événement pluviométrique. L'effet des pratiques est important pour les faibles pluies (Figure 3) : réduction du taux de ruissellement grâce au paillage et au travail du sol, y compris le sillonnage qui augmente les capacités d'infiltration dans le sillon. En revanche, aucun effet des pratiques n'est observé en cas de fortes pluies aboutissant à un ruissellement généralisé. Les résultats ont montré l'intérêt d'analyser les effets des pratiques sur le long terme (deux cycles de culture ici). Ainsi le travail du sol est apparu favorable dans un premier temps et, de façon contre-intuitive, sans effet néfaste du sillonnage dans le sens de la pente du fait de l'augmentation forte de la capacité d'infiltration dans le sillon. Cet effet favorable s'amenuise avec le temps au fur et à mesure du tassement du sol, la gestion de la couverture au sol du fait des restitutions devenant le premier facteur de gestion du ruissellement.

Ces résultats sont importants. Ils montrent tout d'abord que malgré de fortes capacités d'infiltration du sol, du ruissellement est enregistré en parcelle. Si les taux de ruissellement en parcelle sont faibles en moyenne, ils représentent cependant des volumes hydriques élevés en relation avec le niveau de précipitations (3500 mm annuels de pluie sur la zone d'étude). Ces études font surtout ressortir le caractère déterminant des conditions locales qui ont une influence aux échelles supérieures (parcelle). Leur prise en compte dans les modèles doit permettre d'améliorer la prévision du phénomène ainsi que d'identifier les moyens techniques de le gérer (travaux du sol, paillage…).

Principales publications et rapport relatifs au thème

↳ **Cattan**, P., Cabidoche, Y.-M., Lacas, J.G, Voltz, M. (2006). Effects of tillage and mulching on runoff under banana (Musa spp.) on a tropical Andosol. Soil and Tillage Research. Vol 86, p 38-51.

↳ **Cattan** P., Ruy, S., Cabidoche, Y.-M, Findeling, A., Desbois, P., Charlier, J.-B. (2009). Effect on runoff of rainfall redistribution by the impluvium-shaped canopy of banana cultivated on an Andosol with a high infiltration rate. Journal of Hydrology (IF 2007 2.161), vol 368, p. 251-261

↳ Charlier, J.-B., Moussa, R., **Cattan**, P. and Voltz, M. (2009). Modelling runoff at the plot scale taking into account rainfall partitioning by vegetation: application to stemflow of banana (Musa spp.) plant. Hydrol. Earth Syst. Sci. (IF 2007 2.167), 13(11), p 2151-2168.

↳ Desbois Pierre (2006) Analyse de la variabilité spatiale et temporelle du partage ruissellement - infiltration pour le système sol-bananier à la surface d'un andosol de Guadeloupe à l'échelle locale du bananier. Mémoire de DAA Génie de l'environnement, option eau. Agrocampus Rennes. 31p + annexes

2.1.3 Influence de l'hétérogénéité de couvert et d'entretien du sol sur le drainage

Différentes études notent l'influence de la redistribution de la pluie par les plantes sur la percolation (Paltineanu and Starr, 2000; Starr and Timlin, 2004; Timlin et al., 1992; Van Wesenbeeck and Kachanoski, 1988). Cet aspect n'avait pas été abordé dans le cas de la bananeraie et de la concentration particulièrement forte des écoulements le long de son tronc. Une des difficultés est la mesure du volume drainé à l'échelle locale. Des lysimètres sont souvent utilisés et permettent outre la détermination des volumes drainés, le prélèvement de la solution du sol pour analyse. Leur principe repose sur l'imposition d'une condition de potentiel à l'endroit du prélèvement (on exerce une succion). Le principale inconvénient réside dans les perturbations des écoulements suite à l'implantation du matériel dans le sol et à la représentativité du prélèvement par rapport à l'écoulement réel dans le sol. Deux types de lysimètre existent : ceux à pression atmosphérique (Boll et al., 1991; Goyne et al., 2000; Zhu et al., 2002) et ceux à succion (Boll et al., 1992; Brandi-Dohrn et al., 1996; Brye et al., 1999; Kosugi and Katsuyama, 2004). Les lysimètres atmosphériques ne permettent de collecter les eaux que quand le sol à l'interface du lysimètre est saturé. Ce type de lysimètre ne permet de récolter qu'une fraction du drainage (Boll et al., 1991; van der Velde et al., 2005; Zhu et al., 2002) qui est représentative des écoulements saturés. L'emploi d'un lysimètre à mèche permet d'exercer une succion sur le sol et de se rapprocher du gradient de potentiel réel dans le sol ; il est susceptible d'assurer en théorie un échantillonnage plus représentatif des écoulements dans le sol, en conditions saturées mais aussi non saturées.

Figure 4 : lysimètre composite à mèche (3 cases au centre) et atmosphérique (le reste du plateau) pour la détermination des flux de drainage

Ces études ont été abordées dans le cadre des projets DIREN1, DIREN2 que j'ai animés puis PNRH (voir CV). Elles ont été conduites en partenariat avec les équipes de l'UMR LISAH de Montpellier ainsi que de l'INRA de Guadeloupe et d'Avignon. Les travaux ont été menés dans une première phase sur le dispositif en parcelle de 2001 à 2002. Le principal objectif était d'analyser l'effet de la redistribution sur la variation temporelle et spatiale du drainage. Un second objectif a été d'évaluer l'importance des flux saturés et non saturés en bananeraie à partir des mesures issues de lysimètres atmosphérique et à mèche. Ceci présentait un intérêt notamment dans l'étude de la mobilisation des polluants qui sera abordée par la suite. Ainsi, des lysimètres composites (Figure 4), atmosphériques et à mèche, ont été utilisés et implantés sous les bananiers et entre les bananiers. Les flux ont été mesurés durant plus d'un an à cheval sur deux cycles culturaux. Les travaux conduits à l'échelle du bananier de 2004 à 2005 ont confirmé et précisé les résultats obtenus en 2001 et 2002. Leurs résultats ont été exploités dans le travail de thèse de Julie Sansoulet (Sansoulet, 2007) notamment sous forme d'un travail de modélisation à partir du logiciel HYDRUS 2D et 3D (Simunek et al., 2008).

Les résultats montrent que la mesure des flux de percolation est biaisée dans les deux systèmes lysimétriques (Cattan et al., 2007b) : les flux de drainage sont sous-estimés dans les lysimètres gravitaires et surestimés dans les lysimètres à mèche. Sous le bananier les flux de percolation sont deux fois plus élevés qu'entre les bananiers ; les flux saturés y sont sept fois plus élevés alors qu'ils sont presque absents entre bananiers. Au total 88% de la variance des flux de percolation est expliquée par la variation d'intensité pluviométrique au niveau du sol du fait de la redistribution par les plantes et par l'état hydrique initial du sol.

Ces résultats notamment en termes de variabilité des types de flux en parcelle sont importants car ils conditionnent le transport des éléments solubles vers les horizons profonds du sol. D'un point de vue pratique, le nombre de lysimètres nécessaires pour estimer les flux de percolation en parcelle peut être réduit si l'on tient compte de la répartition spatiale des conditions aux limites.

Principales publications et communication relatives au thème

↳ **Cattan**, P., Voltz, M., Cabidoche, Y.-M., Lacas, J.G, Sansoulet, J. (2007) Spatial and temporal variations in percolation fluxes in a tropical Andosol influenced by banana cropping patterns. Journal of Hydrology, vol 335: n° 1-2, 157-169.

↳ Sansoulet, J., Cabidoche, Y.-M., **Cattan**, P., Ruy, S., Simunek, J. (2008). Spatially Distributed Water Fluxes in an Andisol under Banana Plants: Experiments and Three-Dimensional Modeling. Vadose Zone Journal. 7(2), p 819-829.

↳ Lacas, J.G., Voltz, M., **Cattan**, P. (2004). Numerical evaluation of passive capillary samplers. European Geosciences Union. 1st General Assembly Nice, France, 25 - 30 April 2004

↳ Lacas, J.G., Voltz, M., **Cattan**, P., Louchart, X. (2004). Passive capillary pan samplers: an efficient system to monitor in-situ percolation fluxes in soils. System presentation and estimation of measurement uncertainties. COST Action 629 workshop; Water pollution in natural porous media at different scales: fate, impact and indicators, Louvain- la-Neuve, Belgium, October 21-22, 2004.

Ainsi la redistribution de la pluie par le couvert végétal induit une hétérogénéité des flux à la surface et dans le sol. Or les pratiques d'épandage sont également hétérogènes en bananeraie et de nombreux intrants (insecticides contre le charançon, nématicides, voire engrais) sont appliqués au pied du bananier, c'est-à-dire là ou les flux sont concentrés par la plante, là où les flux en drainage sont maximum et là d'où part le ruissellement. Ceci a conduit à aborder la question de l'incidence de la redistribution du couvert sur la dispersion des pesticides.

2.2 Mobilisation des pesticides

2.2.1 Quelques éléments concernant le devenir des pesticides dans l'environnement

Le devenir des pesticides dans l'environnement, c'est-à-dire leur rétention, leur transport et leur dégradation, dépend de leurs propriétés ainsi que des caractéristiques des différents milieux concernés, sol, eau, atmosphère. Une brève description des principaux processus sera ici rappelée (d'après (Calvet, 2005) pour lesquels on n'abordera pas le cas des molécules en phase gazeuse alors que le phénomène de volatilisation est limité dans le cas des pesticides utilisés en bananeraie.

Deux ensembles de propriétés des molécules sont plus particulièrement impliquées dans les processus touchant à leur devenir. Les propriétés physicochimiques d'une part qui sont en rapport avec le changement d'état des molécules : solubilité dans l'eau et les solvants organiques (passage de l'état solide ou liquide à l'état dissous), volatilité (passage de l'état solide ou liquide à l'état gazeux), adsorbabilité (passage de l'état dissous ou gazeux à l'état adsorbé). Ces propriétés entrent en jeu dans les processus de rétention de transfert et de biodisponibilité. Les propriétés chimiques d'autre part qui sont en rapport avec la transformation des molécules (ionisation, hydrolyse…) et qui entrent en jeu dans le processus de dégradation. Différents groupes fonctionnels orientent ces propriétés : par exemple le groupe hydrophobe méthyle (CH_3) induira une plus forte affinité pour les lipides et une forte solubilité dans les solvants organiques ; la présence d'un atome de Chlore (Cl) (famille des organochlorés) pourra se traduire par une dégradation lente et une affinité pour les lipides …

La rétention conditionne la mobilité des pesticides dans les sols. Le coefficient de distribution Kd, qui est le rapport des concentrations d'un pesticide entre le sol et l'eau, et son expression normalisée Koc (c'est-à-dire le Kd par unité de fraction de carbone organique du sol) rendent compte de l'affinité d'un pesticide pour un sol. Les molécules pesticides adsorbées sont susceptibles de repasser dans la solution du sol et de redevenir mobilisables. C'est le cas lors de la modification de la composition de la solution du sol (phénomène de désorption) ou des caractéristiques de la phase solide (transformation de la matière organique par exemple). Une hystérésis peut-être observée, le pesticide étant plus facilement adsorbé que désorbé.

La capacité des pesticides à se dégrader dans le milieu est un élément clé de l'impact environnemental des pratiques. La dégradation résulte de transformations chimiques qui modifient la composition et la structure des molécules apportées au sol. Elle peut conduire à divers produits de transformation, gardant ou non un caractère létal pour les organismes, voire à la minéralisation complète de la molécule de départ. La dégradation est de nature abiotique (hydrolyse, oxydation et réduction, réactions photochimiques) ou biotique. La période de demi-vie qui est le temps nécessaire à l'obtention d'une concentration égale à la moitié de la concentration de départ (elle est calculée en admettant une cinétique de disparition de premier ordre), permet de rendre compte de la persistance chimique de la molécule dans le milieu.

Les pesticides en solution sont entraînés par les eaux soit par voie de surface (ruissellement) soit dans le sol par percolation. Au sein de la matrice, l'eau de percolation circule dans des pores de taille variée (diamètre allant du nanomètre au millimètre). La circulation dans des pores de grandes tailles ou macropores (plus de 75 µm de diamètre - (Brewer, 1964) est à l'origine d'un flux rapide en profondeur qualifié de préférentiel. Différents travaux montrent l'incidence des flux de drainage préférentiels sur la mobilisation des pesticides (Abbaspour et al., 2001; Katterer et al., 2001; Magesan et al., 1995).

2.2.2 Le cas des Antilles

La dispersion d'un nématicide a été étudiée dans le cadre d'une bananeraie installée sur Andosol. Concernant le type de sol, différentes spécificités sont à souligner. En premier, lieu, les modes de rétention sont variés : adsorption mettant en jeu des liaisons ioniques du fait des capacités d'échange anionique et cationique du substrat jusqu'aux interactions hydrophobes en relation avec les teneurs élevées en matière organique ; séquestration physique des molécules en raison de la structure porale particulière du matériaux (Dorel et al., 2000; Woignier et al., 2007). Du fait de ces caractéristiques il apparaît possible que des molécules non ionisables, polaires comme les organophosphorés où apolaires comme les organochlorés, soient fortement fixées. D'autre part du point de vue transport, des voies préférentielles ont été mises en évidence dans les sols volcaniques (Clothier et al., 2000; Poulenard et al., 2004) et s'accordent sous certaines conditions avec les résultats que nous avons trouvés en matière de flux saturés. Concernant la molécule, le cadusafos, nématicide organophosphoré, a été plus particulièrement étudié. Le caractère hydrophobe de la molécule, qui comporte 5 groupes méthyles, est révélé pas la valeur élevée du coefficient de partage octanol/eau (3.85) ainsi que du coefficient de partage normalisé Koc (227 ml g^{-1}). La molécule est peu volatile et aucune dissociation n'est notée ; elle est considérée comme stable dans l'eau. Sa persistance est modérée et sa période de demi-vie est évaluée à 39 jours au champ. Le cadusafos, comme de nombreux intrants en bananeraie, est appliqué au pied du bananier dans une zone de départ de ruissellement et de fort drainage. La combinaison d'une hétérogénéité des pratiques à celle des flux présente ici un risque maximum vis-à-vis des atteintes à l'environnement pour cette molécule.

Nos études ont été abordées dans le cadre des projets DIREN1 et DIREN2 (voir CV). Elles ont été conduites en partenariat avec les équipes de l'UMR LISAH de Montpellier ainsi que de l'INRA de Guadeloupe. Les travaux ont été menés sur le dispositif en parcelle de 2001 à 2002. On s'est attaché à établir l'influence des types de flux en bananeraie sur la mobilisation d'un nématicide, le cadusafos épandu au pied du bananier.

Les résultats montrent (Saison et al., 2008) qu'à l'échelle de la parcelle les pertes par drainage sont majoritaires (0.34% des pesticides appliqués) par rapport au ruissellement (0.13%). Ces pertes relativement faibles ne doivent pas cacher les risques de pollution événementielle en raison de concentrations pouvant atteindre 1000 µg L^{-1} dans les eaux de circulation rapide, d'autant plus que la fréquence des traitements est élevée (jusqu'à 4 par an). L'influence de la redistribution de l'eau par la plante est observable à deux niveaux : d'une part 67% des pertes se situe au pied du bananier ; d'autre part le transport s'effectue majoritairement par les flux saturés bien qu'ils soient

5 fois moins importants que les flux totaux de percolation. Ces pollutions restent fugaces et diminuent rapidement dans le temps. Ainsi, les pertes les plus importantes ont été enregistrées au cours des trois premières semaines suivant l'application. Ceci est dû à une période de demi-vie de la molécule particulièrement courte (7 jours dans les conditions de l'expérimentation) ainsi que par une forte rétention de la molécule dans les horizons de surface à forte teneur en matière organique (6% de C organique) ce qui est cohérent avec le caractère hydrophobe de la molécule. Cependant une contamination de niveau faible est par la suite enregistrée et perdure jusqu'à la fin de l'expérimentation.

Ces résultats sont essentiels. Ils constituent à notre connaissance la seule référence de comportement d'un pesticide établi en bananeraie sur sol volcanique en milieu tropical. Ils montrent que l'influence de la redistribution de la pluie par le bananier, notamment du fait des flux saturés engendrés au pied de la plante, augmente la mobilisation des pesticides vers les horizons profonds des sols. Ces résultats ont été confirmés par ceux obtenus dans le cadre de la thèse de Julie Sansoulet (Sansoulet, 2007) pour la fertilisation : outre des exportations préférentielles au pied du bananier, ils ont notamment montrés que la délocalisation des épandages permettait de réduire les quantités exportées. Ces caractéristiques diffèrent des situations habituellement reportées par la littérature. Une conséquence est par exemple que dans ces conditions de forte infiltration, l'utilisation de bandes enherbées recommandées dans les pays tempérés n'apparaît pas ici appropriée.

Travaux publiés dans

↳ Saison, C., **Cattan**, P., Louchart, X., Voltz, M. (in press) Effect of spatial heterogeneities of water fluxes and application pattern on Cadusafos Fate on Banana Cultivated Andosols. Journal of Agricultural and Food Chemistry.

↳

En définitive, ces études à la parcelle montrent de façon exemplaire l'influence déterminante du couvert végétal et de l'itinéraire technique sur l'intensité et la variabilité des flux d'eau et de solutés. Ainsi, d'un point de vue agronomique, les techniques de gestion du couvert végétal doivent être considérées comme un moyen supplémentaire de gestion des transferts en parcelle : gestion de la répartition de l'eau et de l'accès à cette ressource par les différents organismes présents sur la parcelle ; gestion et régulation des exportations de produits polluants. De là, on conçoit que ces techniques peuvent également présenter un moyen de gestion des transferts aux échelles supérieures. Mais comment évaluer l'impact de pratiques appliquées localement sur les transferts à l'échelle des bassins versants ? La section suivante pose les bases d'une réponse.

3 Transport et dispersion des pesticides à l'échelle du bassin versant

C'est à l'échelle du bassin versant que se situent les enjeux d'évaluation de la pollution de la ressource en eau. Or en milieu volcanique, la succession de projections volcaniques hétérogènes produit un milieu souterrain complexe (Falkland and Brunel, 1989). Si quelques études traitent des risques de transfert de pesticides dans les eaux souterraines en milieu volcanique (Bernard et al., 2005), les quelques références disponibles sont cantonnées à l'étude hydrologique dans un contexte de forêts tropicales humides très différent (Fujieda et al., 1997; Lesack, 1993) et ne concernent ni les bassins versant cultivés ni les processus de contamination des eaux. Une question essentielle à examiner est la contribution relative des écoulements de surface et souterrains aux flux de polluants à l'exutoire des bassins et à la recharge de nappe afin de déterminer les voies préférentielles de transfert des polluants dont la préservation est à privilégier.

L'échelle du bassin versant est complexe : différents types de sol, de culture ; complexité du réseau d'écoulement des eaux ; lourdeur des équipements et des outils de caractérisation ; nécessité d'établir des chroniques à long terme... Deux étapes peuvent être distinguées dans les études qui ont été menées. Une première à porté sur la caractérisation du fonctionnement hydrologique d'un bassin d'étude pour identifier les voies de circulation des eaux et quantifier les flux. La seconde étape a consisté à caractériser les facteurs de dispersion du cadusafos au sein des bassins versants à travers d'une part l'étude du comportement de la molécule dans les sols et d'autre part de la caractérisation de son mode de transport au sein du bassin d'étude ainsi que de la pollution résultante des ressources en eau.

Ces études ont été réalisées sur le petit bassin bananier de Féfé d'une 20e d'ha, sous-bassin de la rivière Pérou à Capesterre Belle Eau, Guadeloupe. Elles ont servi de support à la thèse de J.B. Charlier que j'ai co-encadrée avec Roger Moussa et Marc Voltz de l'UMR LISAH. Elles ont été financées par les projets DIREN1 et DIREN2 (voir CV).

3.1 Fonctionnement hydrologique de bassin

L'objectif était donc d'identifier les voies de circulation des eaux et de quantifier les flux. L'approche a emprunté une voie expérimentale et une voie de modélisation. Les résultats ont été interprétés à l'échelle annuelle et à l'échelle de l'événement pluviométrique. La partie expérimentale a porté sur la mesure des précipitations, des débits en sortie de bassin, des fluctuations de nappes et du suivi des caractéristiques physiques du bassin (topographie, occupation du sol, conductivité hydraulique à saturation…). La voie de modélisation à poursuivi deux objectifs. Le premier portait sur la formalisation des résultats à travers l'élaboration d'un modèle à réservoir à l'échelle globale du bassin permettant de simuler les crues et le niveau des nappes. Le second a été basé sur la réalisation d'un modèle spatialisé. Il avait pour but d'une part de tester les hypothèses de fonctionnement du bassin établies à partir des données expérimentales et d'autre part de tester différents scénarios d'aménagement ou d'occupation du sol, préalable à l'évaluation de l'effet des pratiques agricoles sur les écoulements.

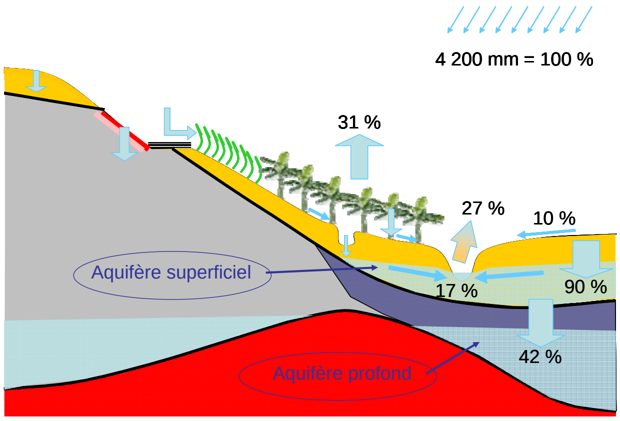

Figure 5 : éléments du bilan hydrologique du petit bassin versant de Féfé (20 ha) (d'après Charlier, 2007)

Les résultats (Charlier et al., 2008) montrent un fonctionnement hydrologique original avec la présence de deux aquifères superposés (Figure 5): un superficiel alimentant la ravine drainant les eaux du bassin et un aquifère profond. L'importance de l'infiltration est l'élément marquant du fonctionnement du bassin : 92% de l'eau précipitée s'infiltre et alimente pour près de la moitié l'aquifère profond (42% des précipitations). L'importance du ruissellement varie selon l'état hydrique du bassin entre 6 et 24% des précipitations à l'échelle de l'événement pluviométrique. Ces taux sont importants par rapport à d'autres bassins occupés par la forêt. Le mode de production du ruissellement est hortonien suivant un schéma identique à celui observé en parcelle expérimentale à Neufchâteau. L'élaboration d'un modèle représentant les principaux réservoirs du bassin a permis de valider les hypothèses de fonctionnement. Le développement d'un second modèle, spatialisé, à partir du modèle MHYDAS (Moussa et al., 2002), adapté au contexte cultivé, a permis de prendre en compte l'organisation spatiale du paysage (réseau de fossés, routes, parcellaire…). Ce modèle est basé sur une segmentation de l'espace prenant en compte l'ensemble des informations disponibles sur le bassin et délimitant des unités hydrologiques, unités de base pour la simulation des phénomènes de transfert. L'approche de modélisation est basée sur un schéma de fonctionnement qui hiérarchise les processus selon les différentes échelles : à l'échelle de la parcelle la redistribution de la pluie par le bananier (stemflow) augmente le ruissellement, à l'échelle du sous-bassin composé de deux parcelles et d'un fossé s'ajoutent les écoulements à surface libre et la réinfiltration vers la nappe, à l'échelle du bassin versant l'ensemble des processus de ruissellement et d'échanges nappe-fossés interagissent. Finalement ce modèle permet de simuler les écoulements en sortie de chaque unité hydrologique ainsi qu'à l'échelle du bassin entier. Différentes simulations ont été réalisées à partir de ce modèle spatialisé (Charlier, 2007). Une première simulation a permis de caractériser les variations de la contribution du ruissellement de surface de l'amont de la ravine jusqu'à l'exutoire. Une autre simulation a permis d'évaluer l'impact de la culture de banane sur les écoulements à l'échelle du bassin. Ainsi, cette culture accroit le ruissellement de surface et provoque une augmentation du débit maximum des crues à l'exutoire du bassin.

Ces résultats sont nouveaux dans le contexte des milieux cultivés sur sols volcaniques en zone tropicale. Ils permettent pour la première fois d'y aborder la question de la gestion des pratiques agricoles à l'échelle des bassins versants. L'effet de la mise en culture et son importance sur le ruissellement hortonien y est indirectement approché en comparant le fonctionnement de notre bassin expérimental à des bassins forestiers tropicaux. La prédominance du ruissellement hortonien sur ces sols très infiltrants constitue également une originalité forte du site d'étude.

<u>*Travaux publiés dans*</u>

↳ Charlier, J.-B., **Cattan**, P., Moussa, R., and Voltz, M. (2008) Hydrological behaviour and modelling of a volcanic tropical cultivated catchment. Hydrological Processes, p 4355-4370.

↳ Charlier, J.-B., Moussa, R., **Cattan**, P., Voltz, M. (2006). Hydrological behaviour of a small tropical catchment on volcanic deposits. In: Geophysical research abstracts. European Geosciences Union General Assembly. Vienne, Austria, 02 - 07 April 2006.

↳ Charlier, J.-B., Moussa, R., **Cattan**, P., Voltz, M. (2007). Hydrological modelling from the plot to the catchment scales in a tropical cultivated area. In: Geophysical research abstracts. Vol 9, European Geosciences Union General Assembly. Vienne, Austria, 2007.

↳ Charlier, J.-B., 2007. Fonctionnement et modélisation hydrologique d'un petit bassin versant cultivé en milieu volcanique tropical. Thèse de Docteur de l'Université de Montpellier II Thesis, Montpellier, 247 pp

3.2 Dispersion des pesticides

3.2.1 Comportement des pesticides dans les sols

On a vu que les processus à l'origine de la dispersion des pesticides dans l'environnement se rapportent à la rétention et dégradation des molécules dans les sols puis à leur mobilisation et transport par les flux de ruissellement et de percolation en surface et au sein du profil de sol pour aboutir à l'ensemble du réseau hydrographique. La forte variabilité spatiale des types de sol liée à celles des conditions pédoclimatiques incitait dans un premier temps à caractériser les paramètres de rétention et de dégradation des pesticides dans les sols. J'ai recherché une collaboration avec le laboratoire Environnement et Grande Culture de l'INA Grignon sur ce sujet dans le cadre du projet DIREN2, collaboration qui s'est formalisée par le co-encadrement d'un DEA (Lazrak, 2005). La partie analytique s'est déroulée en métropole.

Les résultats ont été obtenus sur une toposéquence allant des Andosols d'altitude aux sols brun rouille à halloysite (Nitisols). Ils montrent que dans les sols volcaniques de Guadeloupe, le cadusafos est principalement fixé dans l'horizon superficiel du sol juste après son application. Il se dégrade ensuite rapidement (la moitié du produit est dégradé en 15 jours à 1 mois). Cependant de grandes variations existent selon les horizons du sol. En effet dès que le pesticide migre dans le sol, il est moins bien retenu et sa dégradation est plus lente. De grandes variations existent également en fonction du type de sol : le cadusafos est 10 fois plus fixé dans les Andosols d'altitude que dans les sols brun-rouille à halloysite et sa vitesse de dégradation y est deux fois plus rapide. Ainsi, il apparaît que les risques potentiels de lessivage sur les Andosols d'altitude apparaissent moins élevés que sur les sols de bas de toposéquence (Tableau 1).

Tableau 1: indice de lessivage selon les types de sol (croissant avec l'intensité du lessivage)

		Andosol perhydraté	Andosol	Sol Brun Andique	Sol Brun Rouille à halloysite
Indice lessivage $\log_{10}DT50 * (4-\log_{10}Koc)$	hor. A	1.8	2.1	2.8	2.7
	hor. B	*2.9*	*3.0*	*3.7*	*3.6*

En premier lieu, ces résultats mettent en lumière l'importance des conditions de milieu sur le risque de pollution. Ainsi, la vitesse de migration du pesticide dans le sol est un élément majeur du risque de pollution. Or les conditions de drainage rapide sont souvent réunies en altitude sur la Basse Terre en raison de l'intensité des événements pluvieux - les études rapportées plus haut montrent que ces risques sont notamment accentués en bananeraie pour les épandages au pied des bananiers où les eaux sont concentrées. Ce risque lié au drainage rapide est cependant contrebalancé par un plus faible risque de lessivage enregistré sur les Andosols du fait d'une meilleure rétention et dégradation des molécules. En second lieu, ces résultats sont importants car ces grands traits de comportement s'appliquent à la Chlordécone, molécule fortement hydrophobe, anciennement appliquée en bananeraie pour laquelle on retrouve les mêmes axes de variation en fonction des types de sol. Paradoxalement, il apparaît ainsi possible que les Andosols qui comportent les plus gros stocks de Chlordécone contribuent, à court terme, plus faiblement que les sols de basse altitude à la contamination des eaux et des plantes. En revanche, les stocks des Andosols maintiennent une pression environnementale élevée à long terme.

Ces variations de comportement des molécules ouvrent des pistes vers un raisonnement des pratiques d'épandage en fonction des zones. Cependant, le risque ainsi déterminé reste à l'échelle de la parcelle. Il ne présage en rien de la contribution effective des zones concernées à la pollution des rivières.

Travaux publiés

↳ Lazrak, E.G., 2005. Devenir du cadusafos sur des sols volcaniques de Guadeloupe sous culture bananière. Mémoire de DEA INPL - Agrocampus Rennes - INA PG - ENSAM -INRA, Nancy, 23 pp

↳ **Cattan**, P., Bonin, M. (2008). Gestion des risques environnementaux liés à l'activité agricole en zone bananière Guadeloupéenne. Rapport final de projet, CIRAD, Neufchâteau, Guadeloupe 91p

↳ **Cattan**, P., Barriuso, E., Cabidoche, Y.-M., Charlier, J.-B., Voltz, M. (2008) Quelques éléments clés sur l'origine et le mode de pollution des eaux par les produits phytosanitaires utilisés en agriculture. Les Cahiers de PRAM, Le Lamentin, Martinique, n°7, 13-19.

3.2.2 Transport du cadusafos à l'échelle du bassin versant

Le transport du cadusafos à l'échelle du bassin versant expérimental de Féfé a été étudié au cours de deux campagnes d'épandage réalisées en 2003 et 2006. La dispersion du pesticide a été suivie de la sortie de parcelle jusqu'à l'exutoire du bassin, dans les eaux de ruissellement de surface ainsi que dans les nappes profonde et superficielle.

Les résultats montrent que deux phases successives de contamination des eaux sont observées (Figure 6 - (Charlier et al., 2009a) : une contamination événementielle par pic qui dure moins de 30 jours associée au transport par ruissellement de surface au cours des épisodes pluvieux ; une contamination de type chronique associée au drainage de la nappe superficielle contaminée. Ces modes de contamination reflètent la structure géologique particulière du bassin volcanique étudié. Globalement, les résultats montrent de faibles pertes représentant moins de 0.03% des quantités apportées. Les pertes les plus importantes sont enregistrées durant la période de pollution chronique c'est-à-dire à l'occasion d'un transport essentiellement souterrain plutôt que par ruissellement de surface. Ces résultats sont cohérents avec le comportement du cadusafos mis en évidence en parcelle.

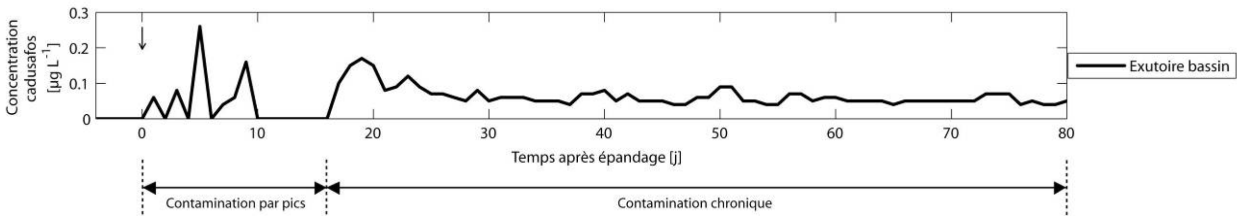

Figure 6 : phases de contamination en sortie de bassin après épandage de cadusafos (d'après Charlier et al., 2009)

Peu d'études de ce type existent en milieu tropical. L'originalité tient à l'importance des transports souterrains. Les principaux enseignements portent tout d'abord sur l'évaluation des pratiques actuelles sur la contamination de la ressource en eau : les sols, les nappes et les eaux superficielles apparaissent contaminés même par les produits actuels se dégradant rapidement. Bien que les concentrations relevées dans les eaux soient faibles le risque d'atteinte du milieu est réel notamment en raison du processus de maturation des pesticides décrit à l'échelle de la parcelle et à l'origine de contamination de faible niveau sur de longue périodes. La complexité des transferts associés à ces pollutions rend particulièrement difficile la délimitation de périmètre de protection de la ressource en eau (captage notamment). Finalement, l'importance des flux hydriques fait que les moyens de contenir ces contaminations sont peu nombreux et résident essentiellement dans la limitation de l'emploi des polluants. Enfin la caractérisation du milieu (notamment structure géologique de bassin) reste un préalable à l'évaluation objective des pratiques agricoles.

Travaux publiés

↳ **Cattan**, P., Bonin, M. (2008). Gestion des risques environnementaux liés à l'activité agricole en zone bananière Guadeloupéenne. Rapport final de projet, CIRAD, Neufchâteau, Guadeloupe 91p

↳ Charlier, J.-B., 2007. Fonctionnement et modélisation hydrologique d'un petit bassin versant cultivé en milieu volcanique tropical. Thèse de Docteur de l'Université de Montpellier II Thesis, Montpellier, 247 pp

↳ Charlier, J.-B., **Cattan**, P., Moussa, R., and Voltz, M. (2009). Transport of a Nematicide in Surface and Ground Waters in a Tropical Volcanic Catchment. Journal of Environmental Quality, vol 38, p 1031-1041.

↳ Charlier, J. B., **Cattan**, P., Voltz, M., Moussa, R. (2009). Transport of a nematicide in surface and ground waters in a farmed tropical catchment with volcanic substratum In: Geophysical research abstracts. Vol 11, European Geosciences Union General Assembly. Vienne, Austria, 200

4 Conclusion

Ces travaux on conduit à l'obtention d'un jeu de résultats importants et nouveaux. Ils constituent un référentiel de base sur les processus de contamination en milieu volcanique tropical : transports souterrains préférentiels ; forte variabilité des capacités de rétention des molécules selon les types de sol ; fortes teneurs en matière organique ; stockage des molécules dans les horizons de surface ; importance des volumes précipités... D'un point de vue scientifique ces résultats apportent un éclairage sur les conditions de mobilisation des pesticides hors des zones tempérées. D'un point de vue agronomique, ces résultats posent la question de la stratégie de traitement à adopter dans des conditions où les molécules peuvent soit se dégrader rapidement soit être fortement adsorbées sur la matrice pour la fraction non dégradée. En effet, dans ces conditions, l'efficacité des produits y est probablement faible (Weber et al., 1993) et les risques d'établissement d'une pollution de type chronique élevés. Ceci justifie la recherche de voies alternatives Quoi qu'il en soit, ces résultats ont eu des conséquences notables dans le cadre de la crise Chlordécone aux Antilles. En premier lieu, d'un point de vue sociétal, l'existence de ce référentiel a fait que les éléments de réflexion sur la mobilité des pesticides étaient disponibles au moment du déclenchement de la crise Chlordécone en Guadeloupe. Il a permis d'apporter des réponses argumentées sur l'origine des pollutions et leur durée probable (Cabidoche, 2006; Cabidoche et al., 2007). D'un point de vue scientifique, ce référentiel a servi de base pour élaborer un modèle d'évolution de concentrations de la molécule dans le sol (Cabidoche et al., 2009). Il a également permis de proposer des actions dans le cadre du projet collaboratif CHLORDEXCO, en réponse à l'appel à projet CES de l'ANR en 2008, qui permettra de mieux appréhender les relations entre exposition et contamination des végétaux et organismes aquatiques pour proposer des méthodes d'exploitation du milieu (choix des plantes à cultiver sur sol contaminé notamment)

Le second point majeur de ces études est sans doute le passage d'une approche globale à une approche spatiale des processus. Ainsi on a vu comment la prise en compte de la variabilité intraparcellaire a permis de mieux comprendre les mécanismes de dispersion des éléments solubles, en l'occurrence un nématicide, aux échelles emboîtées de la parcelle jusqu'au bassin versant. Les études ont montré que la simple redistribution de la pluie par le bananier et la concentration des eaux à son pied combinées avec des pratiques d'épandage localisées favorisaient les exportations de polluants. Cette approche spatiale a permis une avancée notable dans la compréhension des phénomènes par rapport à une approche globale à l'échelle de la parcelle qui avait été retenue jusqu'ici ou qui privilégiait la plante sans s'intéresser plus avant aux interactions avec les parties non cultivées des parcelles. De la même façon, l'approche spatialisée à l'échelle du bassin versant permet seule d'envisager la prise en compte de pratiques agricoles localisées dans le paysage. Le développement d'un modèle d'écoulement spatialisé constitue de ce fait un premier pas vers l'évaluation des impacts environnementaux des pratiques

Enfin, si seule la partie biophysique de l'effet des pratiques a été rapportée ici, une attention particulière a été apportée aux conditions nécessaires à l'évolution de ces pratiques. En préalable, une typologie de fonctionnement des exploitations agricoles bananières a été réalisée

(Dulcire and Cattan, 2002) et a révélé la variabilité des stratégies des exploitants agricoles vouant à l'échec la préconisation d'un conseil unique à l'ensemble des planteurs de banane. Le cas de la jachère a particulièrement été étudié (Bonin and Cattan, 2006; Bonin and Cattan, 2007; Bonin et al., 2006). Il découle de ces travaux qu'une recommandation de réduction des intrants pourra recouvrir de multiples modalités : réduction des doses ; changement d'occupation du sol ; changement de techniques d'épandage… Il faut les outils pour déterminer les conséquences environnementales de cette diversité de réponse à une même recommandation. Ceci met en exergue la nécessité de développer une modélisation spécifique en ce sens.

Chapître 3. Perspectives

1 Introduction

Depuis mon entrée au CIRAD, j'ai toujours recherché un équilibre entre les différentes missions relatives à l'activité de chercheur. Ainsi j'ai pu :

- ⇨ Développer un projet scientifique original et ambitieux sur la caractérisation des impacts environnementaux des cultures en prise direct avec les enjeux de développement.
- ⇨ Construire un partenariat solide et pérenne qui permet d'inscrire mon action au sein d'un réseau de chercheurs nationaux et internationaux.
- ⇨ Accroître mes responsabilités dans le montage / participation à de nombreux projets qui ont financé mes recherches. (10 projets en tout depuis 2000)
- ⇨ Exercer des responsabilités accrues dans la formation : 7 DEA, DAA ou master ; co-encadrement d'un thésard (avec lequel j'ai publié) ; participation à 3 comités de pilotage et à 3 jurys de thèse ; animation de travaux dirigés au sein du DEA Environnement Tropical et Valorisation de la Biodiversité puis du Master Biotrop de l'UAG.
- ⇨ Rendre compte des activités de recherche auprès de la société civile : organisation de restitutions auprès des différents acteurs du milieu agricole montrant notre implication et celle de nos bailleurs.

Actuellement cette dynamique se poursuit autant dans la valorisation des résultats scientifiques, que dans l'encadrement (thèse en cours depuis fin 2008), que dans la recherche de partenariat et le montage de projets. Dans ce dernier cas ceci s'est notamment traduit par le financement du projet CHLORDEXCO présenté à réponse à l'appel à projet CES de l'ANR en 2008 sur la thématique de la Chlordécone. Ce projet a pour ambition (i) de caractériser les déterminants et processus expliquant le degré d'exposition des êtres vivants à la Chlordécone à partir de son stock dans le sol, source des contaminations actuelles ; (ii) d'expliciter la relation existant entre l'exposition à la Chlordécone et la contamination de végétaux destinés à la consommation humaine, d'une part, et celle d'organismes aquatiques ainsi que les conséquences sur leur développement, d'autre part. L'originalité du projet tient dans une approche pluridisciplinaire des problèmes abordés : il mobilise ainsi des compétences en physicochimie du sol, hydrologie, biologie, écotoxicologie et agronomie. Son approche multi-échelle s'étend des conditions locales de relargage de la molécule dans la solution du sol aux impacts des contaminations sur des taxons représentatifs des chaînes trophiques des rivières. Il s'appuie sur les équipes de recherches des Antilles (CIRAD, INRA, UAG), pour leur expérience sur le sujet et leur connaissance des conditions locales, souvent contre-intuitives, et des équipes métropolitaines ou européenne notoires (UMR LISAH de Montpellier, Ecologie et Sante des Ecosystèmes de Rennes et Xénobiotiques de Toulouse, Agrosphere Institute de Jülich en Allemagne) dans leurs compétences scientifiques, notamment méthodologiques.

Les perspectives en termes d'activité scientifique sont associées à ces développements récents et sont déclinées ci-après.

2 A l'échelle de la parcelle, élaboration d'outil d'évaluation et de raisonnement des pratiques culturales

L'objectif de l'agriculture est de modifier les états du milieu dans un sens favorable au développement des cultures en choisissant des itinéraires techniques appropriés. Le contrôle de l'état hydrique du milieu est particulièrement important car il conditionne d'une part la croissance et le développement des êtres vivants au sein de la parcelle et d'autre part les transports de matière (sol, eau, éléments solubles polluants ou non) à l'intérieur et hors de la parcelle. On a vu au cours des travaux exposés que la plupart des pratiques agricoles modifient les états hydriques, et plus généralement le fonctionnement hydrologique des parcelles. Plus précisément, elles modifient le plus souvent de façon hétérogène la répartition en eau au sein des parcelles de même que la distribution des matières solides ou solubles, qu'elles soient fertiles ou polluantes. Ceci peut aboutir localement à une modification profonde des conditions de milieu, qui vont influer sur le développement et la croissance des êtres vivants. Cette hétérogénéité peut-être recherchée : cas des plantations sur billon ou ados, réalisées afin de soustraire la plante à des conditions d'hydromorphie ; goutte à goutte pour optimiser l'alimentation hydrique des plantes ; plantations en cuvette permettant de ramener l'eau vers la plante (Zougmoré et al., 2004)… Cette hétérogénéité peut cependant avoir des conséquences néfastes : création de semelles de labour limitant l'extension et le fonctionnement du système racinaire ; augmentation de l'érosion dans les systèmes avec billon ; non prise en compte de l'hétérogénéité de teneur en eau dans la gestion de l'irrigation aboutissant à des situations d'hydromorphie localisée ; exportation préférentielle d'intrants dans les zones de concentrations des eaux (Derby and Knighton, 2001; Sansoulet et al., 2004) …

Ainsi, les pratiques agricoles génèrent des systèmes hétérogènes complexes à l'échelle de la parcelle. Afin de juger du bien fondé des pratiques mises en œuvre, il apparaît nécessaire d'appréhender l'ensemble des modifications, et en particulier du fonctionnement hydrologique, du système cultivé. Les dispositifs expérimentaux nécessaires pour caractériser des flux d'eau et de matière à l'intérieur ou sortant d'une parcelle sont très lourds à mettre en œuvre (lysimétrie, parcelles de ruissellement…) et nécessitent de travailler sur de longues chroniques. De fait il reste difficile d'évaluer les pratiques agricoles, d'en tester de nombreuses modalités ou encore de nouvelles pratiques. L'utilisation d'un modèle spatialisé représente une solution. L'échelle d'application a le plus souvent été le bassin versant. Des modèles prenant en compte les pratiques existent à l'échelle de la parcelle (Chahinian et al., 2006; Findeling et al., 2003; Takken et al., 2001b; Yu et al., 2000) mais ont rarement été utilisés pour prendre en compte la variabilité intraparcellaire. L'application en bananeraie en a cependant montré l'intérêt pour rendre compte des flux de ruissellement et de drainage en relation avec la concentration de l'eau par la plante. L'échelle d'appréhension des phénomènes est cependant restée trop petite pour rendre compte de l'ensemble du fonctionnement hydrologique en parcelle notamment concernant les phénomènes de réinfiltration en parcelle.

Il existe donc un véritable enjeu à établir un modèle spatialisé de circulation de l'eau en parcelle qui prenne en compte les hétérogénéités liées aux pratiques culturales et permette d'évaluer puis de raisonner ces pratiques. On fait l'hypothèse que la connaissance de la dynamique de l'eau en parcelle et de sa répartition spatiale permettra d'une part d'évaluer les risques de pertes de matière du champ cultivé, soit en terme de fertilité (sol, éléments minéraux) soit en terme de pollution, et d'autre part d'apprécier la variabilité des conditions locales de développement et de croissance des organismes vivants, et donc l'effet probable sur la production des espèces cultivées. Il est possible de s'appuyer sur le modèle spatialisé MHYDAS (Moussa et al., 2002), pour lequel une version incluant le drainage des sols par tuyaux enterrés a été testée (Tiemeyer et al.), et qui a déjà été utilisé dans une approche spatialisée à l'échelle parcellaire (Charlier, 2007; Charlier et al., 2009b; Desbois, 2006).

Pour ce type d'étude, la banane et l'ananas peuvent constituer des plantes de choix : la banane en raison de la forte hétérogénéité spatiale de redistribution de la pluie en bananeraie ; l'ananas comme plante représentative des cultures sur billons et qui peu générer une forte érosion (Khamsouk, 2000). Enfin le cas paradoxal des Andosols sera plus particulièrement traité : forte érosion observée sous certaines conditions de pratiques alors que ces sols sont naturellement peu sensibles à ce phénomène.

Ce travail est important pour aider à construire et évaluer de nouvelles pratiques culturales en parcelle notamment dans des conditions où la ressource en eau est limitante ou bien encore quand les impacts environnementaux des cultures sont préoccupants (pollution sur banane et érosion sur ananas). Il permettra de plus de donner une représentation de l'hétérogénéité des conditions de milieu qui pourra être confronté à la croissance et au développement des végétaux et autres organismes en parcelle.

3 A l’échelle du bassin versant, élaboration d’un outil d’évaluation de l’impact des pratiques agricoles sur la contamination des ressources en eau

Actuellement la montée en puissance de la problématique environnementale s’accompagne d’une forte demande sur les méthodes d’évaluation des pratiques agricoles : responsabilité des pratiques dans la pollution des eaux aux Antilles et en Europe mais aussi en Amérique centrale (exemple de Belize sur des bassins versants occupés en banane) et plus généralement dans l’ensemble des pays émergents, confrontés aux normes de qualités imposés par leurs partenaires occidentaux. On a vu que les références expérimentales étaient très réduites tant au plan des processus de dispersion des matières actives utilisées sur cultures tropicales qu’au plan des impacts biologiques sur les organismes tropicaux. Les dispositifs de monitoring lourds et couteux utilisés pour caractériser l’état de pollutions des milieux ne peuvent que constater des évolutions temporelles mais restent inopérants pour en identifier les causes notamment anthropiques ou naturelles : s’agit-il d’un effet du volume pluviométrique ? D’une dissipation plus importante des molécules en raison d’une mesure éloignée de la période d’épandage ? De quantités moindres épandues ? … Ainsi, il est difficile d’évaluer objectivement l’étendue des contaminations et des risques d’impacts et, d’autre part, de proposer des solutions permettant de limiter l'étendue des contaminations : par exemple modalités d'apport en parcelle (dates, fréquences, zones d'épandage…) ; implantation de couvertures végétales modifiant le partage ruissellement infiltration ou pouvant favoriser la rétention et la dégradation des molécules.

Une voie possible d’évaluation de l’impact des pratiques agricoles est d’utiliser un outil de modélisation intégrant la dynamique des pesticides (par exemple dégradation, relargage progressif par le sol en fonction du volume pluviométrique) sur des périodes longues et selon des conditions climatiques variées. Cette idée est déjà appliquée à l’échelle locale. Ainsi, au plan de l'homologation environnementale des produits phytosanitaires à l'échelle européenne ce sont des simulations par un modèle de transfert de pesticides dans les sols qui sont demandées en complément de mesures lysimétriques. Une démarche similaire appliquée à l'échelle du bassin versant permettrait entre autres d'identifier les voies majeures de transfert alors qu'on ne peut mesurer directement la contribution des écoulements souterrains et de surface au débit des rivières. Elle permettrait surtout de comparer différentes occupations du sol, différents calendriers de traitements et plus généralement différents scénarios de gestion du milieu et ainsi d'opérer un choix raisonné d'actions à promouvoir.

L'enjeu est ici de développer (i) un modèle de référence de transfert des pesticides à l'échelle de bassin versant adapté aux spécificités du milieu tropical volcanique et (ii) une approche d'évaluation des risques aux différentes échelles de l'écosystème.

De tels travaux ont été réalisés dans différentes situations en pays tempérés et ont conduit à la mise au point de modèles spatialisés ou non, pouvant être adossés à des transferts de polluants (par exemple (Louchart et al., 2001). Les hypothèses de fonctionnement sur lesquels ils sont basés sont cependant éloignées de celles des milieux tropicaux, notamment en milieu volcanique dont les principales spécificités sont l'importance de flux hydrique (de 2 à 10 m d'eau en Guadeloupe suivant l'altitude par exemple), l'importance du drainage (90% de l'eau s'infiltre), les capacités de sorption des molécules dans le sol en relation avec des taux de carbone pouvant atteindre 9%, et la permanence des cultures et des traitements phytosanitaires en raison d'un saisonnalité climatique peu marquée. Cependant, on dispose à l'issue des travaux exposés précédemment d'une base de données suffisante pour implémenter, paramétrer et valider une fonction de transfert de pesticide au modèle hydrologique existant.

Différentes questions subsistent et doivent être abordées. Elles sont liées d'une part à la construction du modèle et d'autre part à son utilisation pour des situations différentes.

⇨ Le modèle doit être apte à rendre compte des écoulements de surface et souterrains et de la dispersion des pesticides par ces voies.

⇨ Le modèle doit être adapté à une utilisation opérationnelle sur des pas de temps compatibles avec l'évaluation des systèmes de culture et l'exposition des organismes vivants. Un modèle fonctionnant à l'échelle de l'année hydrologique est ainsi nécessaire. Elle nécessite de contribuer à la prise en compte de cette dimension dans le modèle spatialisé MHYDAS.

- ⇨ Les conditions d'extension du modèle devront être déterminées : d'une part extension à d'autres bassins en établissant une typologie de fonctionnement de bassin ; d'autre part d'extension spatiale en proposant une méthode d'agrégation de sous bassins pour reconstituer les flux résultants.
- ⇨ Le modèle devra être étendu à d'autres molécules présentant un enjeu vis-à-vis de l'environnement. En effet, les premiers résultats ont été établis pour la molécule de cadusafos. Or l'évolution de l'utilisation des molécules est rapide et les besoins de modélisation doivent s'appliquer à différentes molécules. En particulier aux Antilles, le cas de la Chlordécone, un insecticide organochlorés persistant, est préoccupant. Le modèle devra être validé pour cette molécule qu'on peut considérer comme un type de contamination d'un produit non polaire persistant mettant en jeu principalement des liaisons de type hydrophobes. Les questions afférentes à cette molécule portent : (i) sur la contribution des particules solides à la pollution des rivières (transport en phase adsorbée) ; (ii) sur la relation entre les teneurs et stocks dans les sols et la pollution des masses d'eau afférentes (les stocks dans les sols sont la seule source de contamination car cette molécule n'est plus utilisée).
- ⇨ Enfin la pertinence de l'utilisation d'un tel modèle à des fins d'évaluation des pratiques devra être déterminée. Pour cela différents scénarios d'occupation du sol basé sur les évolutions récemment constatées devront être testés.

Ces questions seront abordées dans le cadre du projet CHLORDEXCO ainsi que d'une thèse co-encadrée avec l'UMR LISAH de Montpellier (F. Colin et M. Voltz encadrants), poursuivant ainsi une collaboration engagée sur le long terme.

4 A l’échelle du bassin : déterminants des pratiques et de la charge en polluant

Disposer d’un outil d’évaluation des pratiques reste de peu d’intérêt si ces mêmes pratiques sont insuffisamment caractérisées d’un point de vue technique ou encore si leur zone géographique d’application est imprécise. C’est souvent le cas dans les pays du Sud, voire dans certaines régions de pays du Nord, où les statistiques agricoles se sont mises en place tardivement et restent parfois encore incomplètes. C’est par exemple le cas aux Antilles pour les pratiques d’épandage de pesticides qui peuvent être à l’origine d’une pollution durable des sols et des ressources en eau. Il en est ainsi de molécules actuelles (glyphosate et son produit de dégradation AMPA) ou retirées du marché (Chlordécone - HCH - aldicarbe) qui ont pu poser, posent où poseront un jour problème, et pour lesquelles le niveau de pollution des sols ne peut être approché que par analyse avec les coûts et la lourdeur de gestion que cela comporte. Pour résumer, l’évaluation des conditions aux limites pour les pesticides (apport direct par les agriculteurs, état de contamination des sols et dynamique de relargage des molécules) est un des principaux points d’achoppement de l’évaluation des pollutions agricoles à l’échelle des bassins versants.

Pour résoudre ce problème, des enquêtes de pratiques et d’état de contamination s’avèrent nécessaires. Elles restent cependant non exhaustives en raison des coûts humain et financier qu’elles impliquent. Pour pallier ces inconvénients, des méthodes d’interpolation ont été recherchées. Ainsi, dans le cas de la contamination des sols à la Chlordécone, des premiers travaux ont permis de proposer une carte des risques de contamination en se basant sur l’emprise de la bananeraie au cours des années d’utilisation de cette molécule. Cependant la variabilité des pratiques et notamment d’intensification du système de culture n’a pu être prise en compte dans ce modèle ; or des enquêtes réalisées par ailleurs ont montré que ce facteur était déterminant (Cabidoche et al., 2009). De plus les résultats n’ont pu être organisés selon une logique de dispersion des molécules dans le milieu, notamment en fonction de leur organisation au sein de bassins versants, empêchant in fine toute évaluation de la contamination par dispersion du polluant.

L'enjeu consiste donc ici à élaborer un outil méthodologique ou modèle d'évaluation du degré d'utilisation de produits phytosanitaires par les agriculteurs. Ce travail repose sur l'hypothèse qu'il existe une très grande variabilité des pratiques d'apports selon les agriculteurs. Ces pratiques dépendent du processus de production, et la charge polluante peut être expliquée par : (1) la stratégie de lutte adoptée par l'exploitant agricole ; (2) l'orientation culturale de l'exploitation ; (3) le système de culture (Houdart, 2005). Donc, il apparaît possible de rendre compte des pratiques d'épandage à partir de leurs déterminants, souvent plus simples d'accès à grande échelle que les quantités, doses, fréquences et types de pesticides utilisés.

Ainsi, on cherchera à identifier par enquête les déterminants des pratiques agricoles ayant trait aux apports de produits phytosanitaires. Une méthode d'évaluation des apports sera élaborée sur la base de ses déterminants qu'ils soient endogènes à l'exploitation (processus de production) ou exogènes (par exemple influence du conseil technique) et de leur logique de spatialisation (par exemple aide spécifique au développement de la banane en zone de Montagne induisant l'utilisation de pesticides). Le cas des Antilles et de la Chlordécone sera retenu. La méthode d'évaluation des apports élaborée devra permettre de poursuivre la validation de la carte des contaminations à la Chlordécone et à terme d'étendre cette méthode à d'autres molécules. Ce travail sera engagé dans le cadre des actions prévues au Plan National Chlordécone en collaboration avec l'UMR LISAH et l'INRA APC.

5 En conclusion…

Si le 20^{e} siècle a été celui du développement technologique, l'enjeu du 21^{e} porte certainement sur la préservation de l'environnement. L'immensité des questions soulevées dépasse notre programme de recherche. Sous l'impulsion des pouvoirs publics, la demande de solutions voir de connaissances est portée par les producteurs désirant respecter les nouvelles normes : comment diviser les intrants par 2 ;

comment éviter le rejet d'eau chargées en fongicide en sortie de hangar… Des réponses ponctuelles à ces questions pourront être recherchées (cas du système biobed - (de Roffignac et al., 2008) pour les eaux en sortie de hangar par exemple. Au-delà, l'urgence des demandes se traduit déjà par une multiplication des méthodes d'évaluation des impacts à base biophysique ou non. Il existe un fort enjeu sur la façon de faire cohabiter ces différentes méthodes (Analyse du Cycle de Vie, indicateurs synthétiques, modèles biophysiques) de façon à proposer aux décideurs des outils dont les limites et la fiabilité sont clairement identifiées. Plus ou moins directement, les activités engagées devront participer à alimenter le débat autour de ces indicateurs et méthodes et à proposer des outils sinon de décision, du moins de réflexion pour une meilleure gestion du milieu.

Chapître 4. Références bibliographiques

Abbaspour, K.C., Kohler, A., Simunek, J., Fritsch, M. and Schulin, R., 2001. Application of a two-dimensional model to simulate flow and transport in a macroporous agricultural soil with tile drains. Eur J Soil Science, 52(3): 433-447.

Aubertot, J.N. et al., 2005. Pesticides, agriculture et environnement : réduire l'utilisation des pestyicides et limiter leurs impacts environnementaux, INRA, CEMAGREF.

Basher, L.R. and Ross, C.W., 2001. Role of wheel tracks in runoff generation and erosion under vegetable production on a clay loam soil at Pukekohe, New Zealand. Soil and Tillage research, 62: 117-130.

Beck, A.J., Stolting, H., Harris, G.L., Howse, K.R. and Jones, K.C., 1996. Leaching of recently applied and aged residues of the herbicides atrazine and isoproturon through a large, structured... Chemosphere, 33(7): 1297-1305.

Bernard, H., Chabalier, P.F., Chopart, J.L., Legube, B. and Vauclin, M., 2005. Assessment of Herbicide Leaching Risk in Two Tropical Soils of Reunion Island (France). J Environ Qual, 34(2): 534-543.

Boll, J. et al., 1991. Water quality sampling under preferential flow conditions. In: R.G.A.e. al. (Editor), Lysimeters for evapotranspiration and environmental measurements. Proc. ASCE Int. Symp. Lysimetry, Honolulu, Hawaï. 23-25 July 1991. AM. Soc. Civ. Eng., New York, pp. 290-298.

Boll, J., Steenhuis, T.S. and Selker, J.S., 1992. Fiberglass wicks for sampling of water and solutes in the vadose zone. Soil Science Society of America Journal, 56(3): 701-707.

Bonan, H. and Prime, J.L., 2001. Rapport sur la présence de pesticides dans les eaux de consommation humaine en Guadeloupe. rapport n°2001-070, Ministère de l'aménagement du territoire et de l'environnement - Ministère de l'emploi et de la solidarité, Paris, France.

Bonin, M. and Cattan, P., 2006. Pratiques de jachère et dispositifs d'appui en production bananière guadeloupéenne. Fruits, vol.61:n°2: 83-98.

Bonin, M. and Cattan, P., 2007. Gestion des risques environnementaux liés à l'activité agricole en zone bananière Guadeloupéenne : référentiels environnementaux des principales cultures, CIRAD, Paris.

Bonin, M., Cattan, P., Dorel, M. and Malézieux, E., 2006. L'émergence d'innovations techniques face aux risques environnementaux. Le cas de la culture bananière en Guadeloupe : entre solutions explorées par la recherche et évolution des pratiques; between solutions explored by research and evolution of practices, Agronomes et innovations : 3ème édition des entretiens du Pradel. Actes du colloque des 8-10 septembre 2004. - Paris : L'Harmattan, 2006. Les Entretiens du Pradel, Journées Olivier de Serres. 3, 2004-09-08/2004-09-10, Mirabel, France, pp. 123-135.

Brandi-Dohrn, F.M., Dick, R.P., Hess, M. and Selker, J.S., 1996. Field evaluation of passive capillary samplers. Soil Science Society of America Journal, 60: 1705-1713.

Brewer, R., 1964. Fabric and Mineral Analysis of Soils, New York.

Bromley, J., Brouwer, J., Barker, A.P., Gaze, S.R. and Valentine, C., 1997. The role of surface water redistribution in an area of patterned vegetation in a semi-arid environment, south-west Niger. Journal of Hydrology, 198(1-4): 1-29.

Brye, K., Norman, J., Bundy, L. and Gower, S., 1999. An equilibrium tension lysimeter for measuring drainage through soil. Soil Science Society of America Journal, 63(3): 536-543.

Bussière, F., Solmon, F. and Fouéré, A., 2002. Implementation and evaluation of DROP, a model for the simulation of rainfall distribution below plants described in 3D. Agronomie, 22: 93-103.

Cabidoche, Y.-M., 2006. Stockage dans les sols et dissipation dans les eaux de zoocides organochlorés autrefois appliqués en bananeraies aux Antilles : relation avec les systèmes de culture, INRA - CIRAD, Petit Bourg.

Cabidoche, Y.-M. et al., 2009. Long-term pollution by chlordecone of tropical volcanic soils in the French West Indies: A simple leaching model accounts for current residue. Environmental Pollution. Special Issue Section: Ozone and Mediterranean Ecology: Plants, People, Problems, 157(5): 1697-1705.

Cabidoche, Y.M. et al., 2007. Devenir de pesticides organochlorés persistants dans les sols antillais : le cas de la chlordécone., Evaluation et réduction des risques liés à l'utilisation des pesticides. INERIS, Reims, France.

Calvet, R., 2005. Les pesticides dans le sol. Conséquences agonomiques et environnementales, 637 pp.

Carrouee, B., Dore, T., Laconde, J.P., Ney, B. and Schmutz, T., 1989. Interprétation des variations du rendement du pois. Premiers acquis sur l'élaboration du rendement du pois et méthodes d'evaluation. Congrès : Journée Nationale des Proteagineux. Atout Pois (Paris). ITCF (Paris), 1989-02-09: 5-17.

Casenave, A., 1991. Spécificité des processus du ruissellement en zone sahélienne. Influence des états de surface. In: ORSTOM (Editor), Utilisation rationnelle de l'eau des petits bassins versants en zone aride. AUPELF-UREF, John Libbey Eurotext, Paris, pp. 77-86.

Castillo, L.E., Ruepert, C. and Solis, E., 2000. Pesticide residues in the aquatic environment of banana plantation areas in the north Atlantic zone of Costa Rica. Environmental Toxicology and Chemistry, 19(8): 1942-1950.

Cattan, P., 1994. Quelques elements du diagnostic cultural chez l'arachide hative. Proc atelier arachide ICRISAT, Niamey, novembre 1994.

Cattan, P., 1996. Les composantes du rendement de l'arachide. Agriculture et developpement, 11: 33-38.

Cattan, P., Bussiere, F. and Nouvellon, A., 2007a. Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation. Hydrological Processes, 21(16): 2196-2205.

Cattan, P., Cabidoche, Y.-M., Lacas, J.-G. and Voltz, M., 2006. Effects of Tillage and mulching on runoff under banana (Musa spp.) on a tropical Andosol. Soil and Tillage Research, 86(1): 38-51.

Cattan, P. and Fleury, A., 1998. Flower production and growth in the groundnut plants. European Journal of Agronomy, 8: 13-27.

Cattan, P. et al., 2009. Effect on runoff of rainfall redistribution by the impluvium-shaped canopy of banana cultivated on an Andosol with a high infiltration rate. Journal of Hydrology, 368(1-4): 251-261.

Cattan, P., Voltz, M., Cabidoche, Y.-M., Lacas, J.-G. and Sansoulet, J., 2007b. Spatial and temporal variations in percolation fluxes in a tropical Andosol influenced by banana cropping patterns. Journal of Hydrology, 335(1-2): 157-169.

Chahinian, N., Moussa, R., Andrieux, P. and Voltz, M., 2006. Accounting for temporal variation in soil hydrological properties when simulating surface runoff on tilled plots, Journal of Hydrology, pp. 135-152.

Charlier, J.B., 2007. Fonctionnement et modélisation hydrologique d'un petit bassin versant cultivé en milieu volcanique tropical. Thèse de Docteur de l'Université de Montpellier II Thesis, Montpellier, 247 pp.

Charlier, J.-B., Cattan, P., Moussa, R. and Voltz, M., 2008. Hydrological behaviour and modelling of a volcanic tropical cultivated catchment. Hydrological Processes, 22(22): 4355-4370.

Charlier, J.-B., Cattan, P., Voltz, M. and Moussa, R., 2009a. Transport of a Nematicide in Surface and Groundwaters in a Tropical Volcanic Catchment

10.2134/jeq2008.0355. J Environ Qual, 38(3): 1031-1041.

Charlier, J.B., Moussa, R., Cattan, P., Cabidoche, Y.M. and Voltz, M., 2009b. Modelling runoff at the plot scale taking into account rainfall partitioning by vegetation: application to stemflow of banana (Musa spp.) plant. Hydrol. Earth Syst. Sci., 13(11): 2151-2168.

Cheng, H.H., 1990. Pesticides in the Soil Environment: Processes, Impacts, and Modeling. ed. Hardcover.

Clermont Dauphin, C., Cabidoche, Y.-M. and Meynard, J.-M., 2004. Effects of intensive mono-cropping of bananas on properties of volcanic soils in the uplands of the French West Indies. Soil Use and Management, 20: 105-113.

Clothier, B.E., Vogeler, I. and Magesan, G.N., 2000. The breakdown of water repellency and solute transport through a hydrophobic soil. Journal of Hydrology, 231-232: 255-264.

CORPEN, 1997. Produits phytosanitaires et dispositifs enherbés. Etats des connaissances et proposition de mise en oeuvre, CORPEN.

Crockford, R.H. and Richardson, D.P., 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. Hydrological Processes, 14(16-17): 2903-2920.

de Roffignac, L., Cattan, P., Mailloux, J., Herzog, D. and Le Bellec, F., 2008. Efficiency of a bagasse substrate in a biological bed system for the degradation of glyphosate, malathion and lambda-cyhalothrin under tropical climate conditions. Pest Management Science, 64(12): 1303-1313.

Derby, N.E. and Knighton, R.E., 2001. Field-Scale Preferential Transport of Water and Chloride Tracer by Depression-Focused Recharge. J Environ Qual, 30(1): 194-199.

Desbois, P., 2006. Analyse de la variabilité spatiale et temporelle du partage ruissellement - infiltration pour le système sol-bananier à la surface d'un andosol de Guadeloupe à l'échelle locale du bananier., ENSAR - CIRAD - INRA, Rennes, France.

Diaz Diaz, R., Garcia Hernandez, J.E. and Loague, K., 1998. Leaching potentials of four pesticides used for bananas in the Canary Islands. Journal of Environmental Quality, 27(3): 562-572.

Dorel, M., 1991. Problèmes de préparation des sols en bananeraie. Cas des sols à halloysite. Fruits, 46(4): 419-427.

Dorel, M., 1993. Travail du sol en bananeraies : cas des andosols. Fruits, 48(2): 77-87.

Dorel, M., Lafforgue, A., Bretaud, P. and Le Breton, M., 1996. Etude de la contamination des eaux de ruissellement par les pesticides utilisés en bananeraie. Rapport d'exécution du Projet CORDET 93 D A 14, CIRAD FLHOR / ORSTOM, Neufchâteau, Guadeloupe.

Dorel, M., Roger-Estrade, J., Manichon, H. and Delvaux, B., 2000. Porosity and soil water properties of Caribbean volcanic ash soils. Soil Use and Management, 16: 133-140.

Dulcire, M. and Cattan, P., 2002. Monoculture d'exportation et développement agricole durable : cas de la banane en Guadeloupe. Cahiers/Agricultures, 11: 313-321.

Durr, C., 1984. Système de culture et élaboration du rendement du riz (Oryza sativa L.) en Camargue., Thèse de doctorat INA PG, 223 p pp.

Duthion, C., Turc, O., Duc, G. and Millet, B., 1988. Etudes du l'élaboration du rendement chez les protéagineux. Compte rendu de fin d'étude de recherches financées par le Ministère de la Recherche et de l'Enseignement Supérieur., INRA, 36 p pp.

Elliott, J.A., Cessna, A.J., Nicholaichuk, W. and Tollefson, L.C., 2000. Leaching Rates and Preferential Flow of Selected Herbicides through Tilled and Untilled Soil. J Environ Qual, 29(5): 1650-1656.

Falkland, A.C. and Brunel, J.-P., 1989. Regional hydrology and water resources problems of humid tropical islands. In: P. UNESCO, FRA (éd.) (Editor), The Development of Hydrologic and Water Management Strategies in the Humid Tropics : Colloque International, 15-22 juillet 1989, Townsville, AUS, pp. 36.

Findeling, A., Ruy, S. and Scopel, E., 2003. Modeling the effects of a partial residue mulch on runoff using a physically based approach. Journal of Hydrology, 275(1-2): 49-66.

Fleury, A., Combe, L. and Picard, D., 1994. The concept of model plant - Yield elaboration in the main annual crops. Institut National Agronomique Paris Grignon, Thiverval Grignon (France). Chaire d'Agronomie. Ed. Paris (France) : INRA: 7-27.

Fleury, A., Masle, J. and Sebillotte, M., 1982. L'analyse de l'élaboration du rendement, outil de jugement du milieu. Bull. Tech. Inf. "Fertilité du milieu et agric": 370-372.

Fujieda, M., Kudoh, T., de Cicco, V. and de Calvarcho, J.L., 1997. Hydrological processes at two subtropical forest catchments: the Serra do Mar, Sao Paulo, Brazil. Journal of Hydrology, 196(1-4): 26-46.

Goyne, K.W., Day, R.L. and Chorover, J., 2000. Artifacts caused by collection of soil solution with passive capillary samplers. Soil Science Society of America Journal, 64: 1330-1336.

Hawkins, R.H., 1982. Interpretations of source area variability in rainfall-runoff relations. In: V.P. Sing (Editor), Rainfall-runoff relationship, . Water Resources Publications, Fort Collins, pp. 308-324.

Henriques, W., Jeffers, W.D., Lacher, T.E. and Kendall, R.J., 1997. Agrochemical use on banana plantations in Latin America:Pespectives on ecological risk. Environmental Toxicology and Chemistry, 16(1): 91-99.

Herwitz, S.R., 1993. Stemflow influences on the formation of solution pipes in Bermuda eolianite. Geomorphology, 6: 253-277.

Hill, R.L., 1993. Tillage and wheel traffic effects on runoff and sediment losses from crop interrows. Soil Science Society of America Journal, 57: 476-480.

Houdart, M., 2005. Organisation spatiale des activités agricoles et pollution des eaux par les pesticides. Modélisation appliquée au bassin-versant de la Capot, Martinique., Université des Antilles et de la Guyane, Fort de France, Martinique.

Houot, S., Topp, E., Yassir, A. and Soulas, G., 2000. Dependence of accelerated degradation of atrazine on soil pH in French and Canadian soils. Soil Biology & Biochemistry, 32(5): 615-625.

Jeuffroy, M.H., 1987. Influence des hautes températures pendant la floraison sur l'élaboration du rendement du pois (Pisum sativum L.) cv. Solara., INRA DIJON, INA P.G., mémoire de fin d'etude DAA, 51 p pp.

Jimenez, O.F. and Lhomme, J.P., 1994. Rainfall Interception and Radiation Regime in a Plantain Canopy. Fruits, 49(2): 133-139.

Katterer, T., Schmied, B., Abbaspour, K.C. and Schulin, R., 2001. Single- and dual-porosity modelling of multiple tracer transport through soil columns: effects of initial moisture and mode of application. Eur J Soil Science, 52(1): 25-36.

Khamsouk, B., 2000. Influence des systèmes de culture bananiers sur l'érosion, le bilan hydrique et les pertes en nutriments en Martinique (sol brun rouille a halloysite). Thèse de Docteur en Science du sol Thesis, Montpellier, 180 pp.

Kosugi, K. and Katsuyama, M., 2004. Controlled-Suction Period Lysimeter for Measuring Vertical Water Flux and Convective Chemical Fluxes. Soil Science Society of America Journal, 68(2): 371-382.

Lazrak, E.G., 2005. Devenir du cadusafos sur des sols volcaniques de Guadeloupe sous culture bananière. mémoire de DEA Thesis, INPL - Agrocampus Rennes - INA PG - ENSAM -INRA, Nancy, 23 pp.

Legros, J.-P., 2007. Les grands sols du monde. PPUR presses polytechniques.

Lennartz, B., Louchart, X., Voltz, M. and Andrieux, P., 1997. Diuron and simazine losses to runoff water in mediterranean vineyards. Journal of Environmental Quality(26): 1493-1502.

Leonard, J., Ancelin, O., Ludwig, B. and Richard, G., 2006. Analysis of the dynamics of soil infiltrability of agricultural soils from continuous rainfall-runoff measurements on small plots. Journal of Hydrology, 326(1-4): 122-134.

Leonard, R.A., 1990. Movement of pesticides into surface waters. In: H.H. Cheng (Editor), Pesticides in the soil environment: Processes, impacts, and modelling. Soil Science Society of America Book Series, Madison, WI, USA, pp. 303-349.

Lesack, L.F.W., 1993. Water balance and hydrologic characteristics of a rain forest catchment in the central Amazon Basin. Water Resources Research, 29(3): 759-773.

Leterme, P., 1988. COLZA : Physiologie et elaboration du rendement. CETIOM, supplement informations techniques, NE103: 23-33.

Leu, C., Singer, H., Stamm, C., Muller, S.R. and Schwarzenbach, R.P., 2004. Simultaneous Assessment of Sources, Processes, and Factors Influencing Herbicide Losses to Surface Waters in a Small Agricultural Catchment

doi:10.1021/es0499602. Environmental Science & Technology, 38(14): 3827-3834.

Levia, D.F., 2004. Differential winter stemflow generation under contrasting storm conditions in a southern New England broad-leaved deciduous forest. Hydrological Processes, 18(6): 1105-1112.

Levia Jr., D.F. and Frost, E.E., 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. Journal of Hydrology, 274(1-4): 1-29.

Llorens, P. and Domingo, F., 2007. Rainfall partitioning by vegetation under Mediterranean conditions. A review of studies in Europe, Journal of Hydrology, pp. 37-54.

Louchart, X., Voltz, M., Andrieux, P. and Moussa, R., 2001. Herbicide Transport to Surface Waters at Field and Watershed Scales in a Mediterranean Vineyard Area. Journal of Environmental Quality, 30: 982-991.

Magesan, G.N., White, R.E. and Scotter, D.R., 1995. The influence of flow rate on the concentration of indigenous and applied solutes in mole-pipe drain effluent. Journal of Hydrology, 172(1-4): 23-30.

Manfroi, O.J. et al., 2004. The stemflow of trees in a Bornean lowland tropical forest. Hydrological Processes, 18(13): 2455-2474.

McDonald, L., Jebellie, S.J., Madramootoo, C.A. and Dodds, G.T., 1999. Pesticide mobility on a hillside soil in St. Lucia. Agriculture, 72(2): 181-188.

Meynard, J.M. and David, G., 1992. Diagnostic de l'elaboration du rendement des cultures. Cahiers Agricultures, NE1: 9-19.

Morin, J. and Kosovsky, A., 1995. The surface infiltration model. Journal of Soil and Water Conservation, 50(5): 470-476.

Moussa, R., Voltz, M. and Andrieux, P., 2002. Effects of the spatial organization of agricultural management on the hydrological behaviour of a farmed catchment during flood events. Hydrological Processes, 16(2): 393-412.

Munier-Jolain, N., 1994. Etude de la croissance des graines chez le soja de type indéterminé (Glycine max. L. Merrill cv Maple Arrow). Thèse INA PG, 93 p pp.

Navàr, J., 1993. The causes of stemflow variation in three semi-arid growing species of northeastern Mexico. Journal of Hydrology, 145: 175-190.

Ndayiragije, S., 1996. Caractérisation d’une séquence d’altération de sols dérivés de matériaux pyroclastiques sous climat tropical humide des Antilles (Guadeloupe), Université Catholique de Louvain, Louvain la Neuve, Belgium.

Ney, B., Duthion, C. and Turc, O., 1994. Phenological response of pea to water stress during reproductive development. Crop Sci., 34: 141-146.

Paltineanu, I.C. and Starr, J.L., 2000. Preferential water flow through corn canopy and soil water dynamics acress rows. Soil Science Society of America Journal(64): 44-54.

Pigeaire, A., Sebillotte, M. and Blanchet, R., 1988. Water stress in indeterminate soybeans : non critical stage in fruit development. Agronomie, 8(10): 881-888.

Poulenard, J., Michel, J.C., Bartoli, F., Portal, J.M. and Podwojewski, P., 2004. Water repellency of volcanic ash soils from Ecuadorian páramo: effect of water content and characteristics of hydrophobic organic matter. Eur J Soil Science, 55(3): 487-496.

Rao, K.P.C. et al., 1998a. Rainfall infiltration and runoff from an Alfisol in semi-aride tropical India. I. No-till systems. Soil and Tillage research, 48: 51-59.

Rao, K.P.C. et al., 1998b. Rainfall infiltration and runoff from an Alfisol in semi-aride tropical India. II. Tilled systems. Soil and Tillage research, 48: 61-69.

Rawlins, B.G. et al., 1998. Review of agricultural pollution in the Caribbean with particular emphasis on small island developing states. Marine Pollution Bulletin, 36(9): 658-668.

Richard, G., Boizard, H., Roger-Estrade, J., Boiffin, J. and Guerif, J., 1999. Field study of soil compaction due to traffic in northern France : pore spare and morphological analysis of the compacted zones. Soil and Tillage research, 51: 151-160.

Rockström, J., Jansson, P.-E. and Barron, J., 1998. Seasonal rainfall partitioning under runon and runoff conditions on sandy soil in Niger. On-farm measurements and water balance modelling. Journal of Hydrology, 210(1-4): 68-92.

Saison, C., Cattan, P., Louchart, X. and Voltz, M., 2008. Effect of Spatial Heterogeneities of Water Fluxes and Application Pattern on Cadusafos Fate on Banana-Cultivated Andosols. Journal of Agricultural and Food Chemistry, 56(24): 11947-11955.

Sansoulet, J., 2007. Transferts d'eau et des ions potassium et nitrate dans un sol a capacité d'échange anionique sous un couvert redistributeur de la pluie, Institut National Agronomique Paris-Grignon, Paris, 168 pp.

Sansoulet, J. et al., 2004. Solute transfert in an andisol of the French West Indies after application of KNO3 : from the agreggate to the field experiment., COST Action 622 final meeting. Volcanic Soil Ressources in Europe, Reykjavik, Iceland, pp. Rala Report. 214: 111-112 (summary).

Sebillotte, M., 1987. Intérêt de l'agrophysiologie pour le raisonnement des itinéraires techniques en fonction des objectifs de rendement. Illustration sur le cas du blé. Conseil Scientifique de l'INRA, mai: 15 p.

Simunek, J., van Genuchten, M.T. and Sejna, M., 2008. Development and Applications of the HYDRUS and STANMOD Software Packages and Related Codes

10.2136/vzj2007.0077. Vadose Zone J, 7(2): 587-600.

Starr, J.L. and Timlin, D.J., 2004. Using high-resolution soil moisture data to assess soil water dynamics in the vadose zone. Vadose Zone Journal, 3: 926-935.

Takken, I. et al., 2001a. Effects of Tillage on runoff and erosion patterns. Soil and Tillage research, 61: 55-60.

Takken, I., Govers, G., Steegen, A., Nachtergaele, J. and Guerif, J., 2001b. The prediction of runoff flow directions on tilled fields. Journal of Hydrology, 248(1-4): 1-13.

Tiemeyer, B., Moussa, R., Lennartz, B. and Voltz, M., MHYDAS-DRAIN: A spatially distributed model for small, artificially drained lowland catchments, Ecological Modelling.

Timlin, D.J., Heathman, G.C. and Ahuja, L.R., 1992. Solute leaching in crop row vs interrow zones. Soil Science Society of America Journal, 56: 384-392.

Turc, O., 1988. Elaboration du nombre de graines chez le pois proteagineux (Pisum sativum L.). Influence du rayonnement intercepte et application au diagnostic cultural., These de l'USTL, 95 p pp.

van der Velde, M., Green, S.R., Gee, G.W., Vanclooster, M. and Clothier, B.E., 2005. Evaluation of Drainage from Passive Suction and Nonsuction Flux Meters in a Volcanic Clay Soil under Tropical Conditions

10.2136/vzj2005.0011. Vadose Zone J, 4(4): 1201-1209.

Van Wesenbeeck, I.J. and Kachanoski, R.G., 1988. Spatial and temporal distribution of soil-water in the tilled layer under a corn crop. Soil Science Society of America Journal, 52: 363-368.

Vensteelant, J.Y., Trevisan, D., Perron, L., Dorioz, J.M. and Roybin, D., 1997. Frequency of runoff in the annually cropped area of the Leman region France . Relation with the functioning of agricultural cultivations. Agronomie, 17(2): 65-82.

Voltz, M. and Louchart, X., 2001. Les facteurs clés de transfert des produits phytosanitaires vers les eaux de surface. Ingénieries, n° Spécial: 45-54.

Wauchope, R.D. et al., 2002. Pesticide soil sorption parameters: theory, measurement, uses, limitations and reliability. Pest Management Science, 58(5): 419-445.

Weber, J.B., Best, J.A. and Gonese, J.U., 1993. Bioavailability and bioactivity of sorbed organic chemicals. In: G.A. Peterson (Editor), Sorption and Degradation of Pesticides and Organic Chemicals in Soil. Soil Science Society of America, Madison, pp. 153–196.

Weber, J.B., Wilkerson, G.G. and Reinhardt, C.F., 2004. Calculating pesticide sorption coefficients (K"d) using selected soil properties. Chemosphere, 55(2): 157-166.

Woignier, T., Pochet, G., Doumenc , H., Dieudonné, P. and Duffours, L., 2007. Allophane a natural gel with interesting environmental properties. Journal of sol gel science and technology, 41: 25-30.

Woignier, T., Primera, J. and Hasmy, A., 2006. Application of the Diffusion Limited Cluster Agregation Model to natural gels: the allophanic soils. Journal of sol gel science and technology, 40((2-3)): 201-207.

Yu, B., Sombatpanit, S., Rose, C.W., Ciesiolka, C.A.A. and Coughlan, K.J., 2000. Characteristics and Modeling of Runoff Hydrographs for Different Tillage Treatments. Soil Sci Soc Am J, 64(5): 1763-1770.

Zhu, Y., Fox, R.H. and Toth, J.D., 2002. Leachate Collection Efficiency of Zero-tension Pan and Passive Capillary Fiberglass Wick Lysimeters. Soil Science Society of America Journal, 66: 37-43.

Zougmoré, R., Ouattara, K., Mando, A. and Ouattara, B., 2004. Rôle des nutriments dans le succès des techniques de conservation des eaux et des sols (cordons pierreux, bandes enherbées, zaï et demi-lunes) au Burkina Faso. Science et changements planétaires / sécheresse, 15(1).

Chapître 5. Articles choisis

1 Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation

HYDROLOGICAL PROCESSES
Hydrol. Process. (in press)
Published online in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.6588

Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation

Philippe Cattan,[1]* François Bussière[2] and Alban Nouvellon[1]

[1] *CIRAD, UPR Systèmes banane et ananas, Capesterre-Belle-Eau, Guadeloupe, F-97130, France*
[2] *INRA Unité Agropédoclimatique de la zone caraïbe, Domaine Duclos, 97170 Petit-Bourg, Guadeloupe, France*

Abstract:

In this article the effect of redistribution of rainfall by banana on local water fluxes and the possible impact of these fluxes on surface runoff has been studied. First the water redistribution by a banana canopy at three development stages (vegetative, flowering, and bunch stage) was measured. The results showed a considerable stemflow, proportional to the leaf area index (LAI), which represented 18 to 26% of the incident rainfall volume according to the age of the crop. Consequently, the rainfall rate was 28-fold higher at the plant collar for a fully developed banana canopy. For the throughfall, on average, the higher the LAI, the lower the mean throughfall. In addition, the spatial distribution of the throughfall varied according to the distance from the pseudostem. Notably, for the earlier stages, the area between the pseudostem and 0·5 m from it received weak throughfall. Secondly, simulations were carried out with a simple two-compartment model simulating the total surface runoff volume. The simulations showed stemflow combined with the agronomical practice of furrowing has an effect on runoff compared to bare soil. A relative increase in surface runoff volume of three-fold was encountered on a plot with a fully developed banana and a infiltration rate of 60 mm h^{-1}. However, the absolute increase was only a few percentage of the incident rainfall volume, although it represented large water volumes given the tropical rains. These features must be taken into account for hydrological management of such systems. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS rainfall interception; stemflow; banana plant; Andosol; runoff; infiltration rate

Received 16 August 2005; Accepted 10 July 2006

INTRODUCTION

Among hydrological processes, rainfall distribution by plant canopies must be accounted for because it determines the amount of water reaching the soil through vegetation. This water either infiltrates or generates runoff with possible adverse environmental effects. Human activity, especially agriculture, may affect this process and must therefore be investigated. This article deals with the effect of canopy architecture and agricultural practices on water fluxes at the plant scale.

It is widely accepted that rainfall interception by plants leads to preferential water pathways through the canopy (see e.g. Herwitz, 1993; Navàr, 1993; Levia *et al*., 2003). The plant stems are, in many cases, the main pathways for the funnelling of the intercepted rainfall to the soil; this water flow is called 'stemflow'. Redistribution of rainfall also occurs elsewhere in the canopy and leads to large spatial variability in water flux. This variability comes from the close juxtaposition of dripping and protected areas. The partitioning into stemflow and throughfall depends on plant structure (Crockford and Richardson, 2000; Manfroi *et al*., 2004) and climatic conditions during the rainfall (Levia, 2004). The high water flows generated by rainfall interception can cause runoff under forests (Herwitz, 1982) as well as under annuals (Bui and Box, 1992). These distributed water flows may also modify the infiltration patterns into the soil, as shown by studies on annual canopies of row-cropping systems (Timlin *et al*., 1992; Paltineanu and Starr, 2000; Timlin *et al*., 2001). Moreover, these water flows may in some cases lead to increased solute leaching when they coincide with agrochemical application (Parkin and Codling, 1990).

The adverse environmental impact of rainfall partitioning may be enhanced in areas with high rainfall rates or where agronomic practices favour erosion and solute leaching. Intensive cultivation of banana (*Musa* spp.) brings together most of these conditions: bananas are grown with high inputs in industrial plantations on more than 1 million ha in the world, mainly in tropical areas with high rainfall rates. Notably, this is the case in Guadeloupe where banana is cultivated in areas with rainfall rates ranging from 2000 to 4000 mm per year (OSTROM, 1982). In these banana-growing areas, soils are Andosols (FAO, 1990), which have a high and variable saturated hydraulic conductivity (Perret, 1992). This saturated hydraulic conductivity may range from 35 to 350 mm h^{-1} and is especially affected by soil tillage (Dorel *et al*., 2000). Moreover, soil tillage may create surface water pathways that can enhance runoff. This is particularly the case when the furrowing follows the slope, as in many banana plantations where each banana

* Correspondence to: Philippe Cattan, station de Neufchâteau, Sainte Marie, 97130 Capesterre-Belle-Eau, France.
E-mail: philippe.cattan@cirad.fr

plant is planted in a furrow. Therefore, the furrow following the slope forms a compartment hydraulically isolated from the interrow.

As mentioned by Levia *et al*. (2003) and Crockford and Richardson (2000), much work has characterized stemflow of forest trees but little has been done on crops. Only one reference was found dealing with the evaluation of stemflow in a banana canopy: Jiménez and Lhomme (1994) who reported high stemflow rates on plantain. Moreover, to the authors' knowledge, there are no studies on the modifications of rainfall partitioning throughout the plant growth cycle and during the evolution of the banana canopy architecture. The purpose of this paper was to evaluate the impact of rainfall partitioning by a banana canopy on soil water transfer. Both experiments and simulations were used. The experiment consisted of measuring water partitioning at the plant scale in banana plantations at three growth stages. Neither surface runoff nor percolation were measured. For the simulations, the experimental results of rainfall partitioning were used to assess the effect on surface runoff of the spatial heterogeneity of rainfall below the canopy in the case of a major tillage practice, furrowing following the slope. In particular, it was wondered whether the runoff risk depended on growth stage according to various infiltration rates. Finally, possible improvements of agricultural practices are discussed.

MATERIALS AND METHODS

Experimental plots

The experiments were carried out in the 1999 rainy season between June and November at the Neufchâteau experimental station of CIRAD-FHLOR (16°04′38″ N, 61°36′04″ W, elevation 250 m) situated at Capesterre-Belle-Eau on the windward coast of the mountainous part of Guadeloupe (FWI). Mean annual rainfall at the station is 3850 mm and the Penman ETP is 1800 mm yr^{-1}. The soil is an umbric Andosol.

The plots were planted with a Cavendish banana, cv Grande Naine, with a spacing of 2·35 m between rows and between plants on the row. As usual, bananas were planted in furrows following the slope. Banana is a large bulbiferous herbaceous crop that can be cultivated over several successive regrowth cycles. Each banana shoot produces a series of sheathed leaves during the vegetative stage. Each new leaf emerges from the bulb inside the sheath of the previous one. The concentric leaf sheaths form the pseudostem, and the plant crown is made of the verticilated leaves with a petiole and a midrib supporting two wide laminae. When flowering, the inflorescence appears from within the sheath of the last leaf and forms the bunch. At the end of fruit growth, the bunch is harvested, the pseudostem is cut down, and one sucker, previously selected, is allowed to grow, starting a new cycle. Only three to five successive crop cycles are cultivated in industrial crops, mainly to limit soil-born pests.

The evaluation of rainfall partitioning was carried out at three key stages of the crop corresponding to three different banana plots (Figure 1). The earlier plant stage corresponding to vegetative growth (Ve) was planted in July 1997; it began its fourth production cycle and was characteristic of a low leaf area index (LAI) regrowth stage. The second plot, planted in March 1999, was in its first production cycle and was reaching its maximum leaf area just before flowering (Fl). The third plot, planted in November 1998, was also in its first production cycle and was selected for measurements during bunch growth (Bu). The three plots were planted with vitro plantlets that ensured an initial homogeneity of the canopy during the first growth cycle (i.e. for Fl and Bu). However, because of the plant-clearing management after harvest, variations appear progressively in banana plantations throughout the successive regrowth cycles. This was the case on the Ve plot; so, on this plot, the experimental areas chosen were those with plants similar in size and in leaf number.

Stemflow and throughfall measurements

On each plot, stemflow collectors were sealed onto six banana plants. A collector was made of a funnel with an enlarged hole for the pseudostem to pass through. It was made watertight around the pseudostem by a silicon seal. A piece of tubing diverted the water collected by

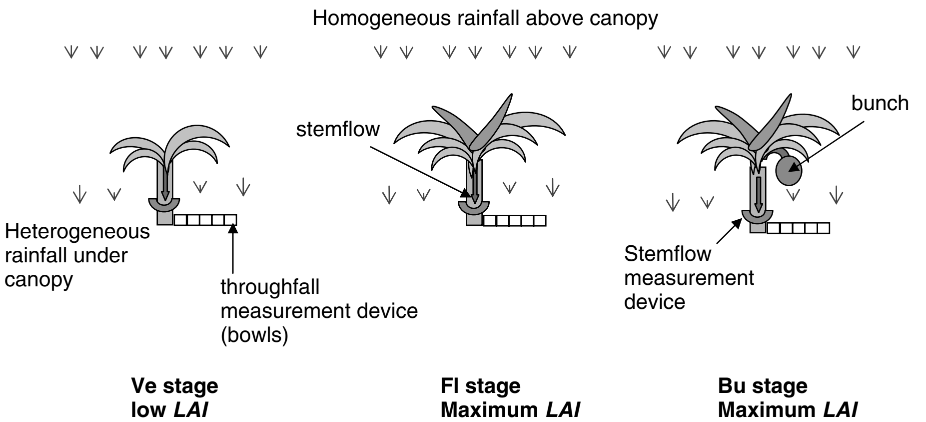

Figure 1. Schematic representation of water fluxes in a banana plant's zone at different growth stages. LAI is the leaf area index

DOI: 10.1002/hyp

the funnel in a series of four 20-l plastic jerry cans that allowed a maximum stemflow recording of 80 l per plant. The stemflow was then expressed by a 'funnelling ratio' (FUN) as introduced by Herwitz (1982), which is the ratio of the stemflow rate—expressed per unit cross-sectional area of the pseudostem at its base, in the present case a mean estimated area of 470 cm^2—to the rainfall rate measured in the open.

The throughfall distribution was measured below the same plants by a matrix of 25 adjacent square bowls ($0{\cdot}23 \times 0{\cdot}23$ m^2, 0·18 m deep, maximum capacity 6·5 l) representing about a quarter of the total theoretical land area per plant (i.e. 2·35 m square—Figure 2). The location of the matrix of bowls was always adjacent to the pseudostem and parallel to the furrow. On this basis, Figure 2 shows that four locations were possible for the matrix. The location was chosen randomly for Ve and Fl, and it was always below the bunch for Bu in order to evaluate the effect of bunch load on water fluxes (Figure 1). Cans and bowls were weighed daily at about 8 : 00 a.m. In the following, the throughfall is expressed, like the stemflow, as a 'transmissivity ratio', that is the ratio of the water volume received in a bowl to the volume of incident rainfall theoretically received above the vegetation on the same area.

The rainfall partitioning measurements were performed successively on the three banana plots. As the stemflow devices were difficult to maintain during plant growth because of stem diameter increase and possible necrosis due to the silicon seal, each experiment was maintained only for 10 rainy days. Finally, as summarized in

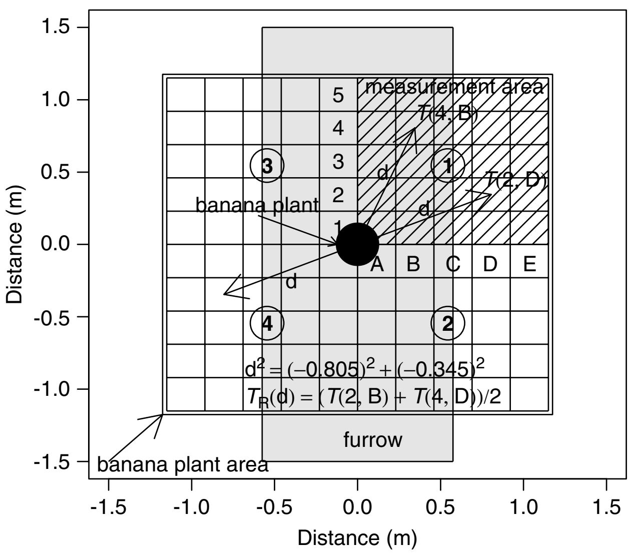

Figure 2. Schematic representation of stemflow and throughfall measurement on one banana plant. The theoretical area for a banana plant ($2{\cdot}35 \times 2{\cdot}35$ m^2) has been divided into a hundred cells of the size of a measurement bowl ($0{\cdot}23 \times 0{\cdot}23$ cm^2). The measurement area is where the bowls were placed to measure throughfall. There were four possible locations (number in circle). $T(x, y)$ was the transmissivity ratio measured for the bowls placed on the cell line x and column y. $T_R(d)$ is the radial transmissivity for the cells at a distance d from the banana plant. $T_R(d)$ was calculated from the average of the bowl transmissivities at d, i.e. T(2,D) and T(4,B) here

Table I, the experiments lasted from 26 July 1999 to 12 August 1999 for Fl (10 rainfall measurements), from 19 August 1999 to 16 September 1999 for Bu (14 rainfall measurements), and from 7–29 October 1999 for Ve (11 rainfall measurements). The leaf area was estimated on 28 July 1999 and on 2, 5, and 10 August 1999 for Fl, on 28 August 1999 and 2, 7 and 10 September 1999 for Bu, and on 11, 20 and 26 October 1999 for Ve.

Rainfall measurements

Rainfall was measured 1 m above the soil in an open area on the plot border in 5-min steps by a tipping bucket (0·2 mm equivalent capacity) rain gauge (ARG100, Campbell Scientific, Shepshed, Leicestershire, UK) connected to a Campbell CR10X datalogger. The rain gauge user guide reported degradation of accuracy of about 4% at rainfall rates of 25 mm h^{-1} and about 8% at 133 mm h^{-1}. Two types of rainfall variables were computed from these measurements. The first variable was the total rainfall between two successive measurements, i.e. at the same steps as the measurements of stemflow and throughfall. The second variable was the rainfall volume per rainfall event, considering a rainfall event as a rainy period in which there was never more than 1 h between two successive tips of the tipping bucket.

Throughout the experiment, the rainfall regime consisted of frequent light falls (80% of rainfalls were less than 5 mm—Figure 3). There were three rainfall events per day and the rainfall duration per event was 10 min (median values). Twenty-five percent of the maximum rainfall intensities at 5-min steps (I_{max}) were higher than 30 mm h^{-1}, and 3% were higher than 60 mm h^{-1} (Figure 3).

Plant measurements

As for many simple-shaped leaves, leaf area can be estimated by allometry. The total leaf area of the six plants used for rainfall distribution measurements on each plot was estimated by a relationship (Equation (1)) established for banana (Champion, 1963):

$$A = 0{\cdot}8\ L\ W \qquad (1)$$

where A is the leaf area (in m^2), L the leaf length (in m), and W the maximum leaf width (in m). The shape factor of 0·8 was previously checked for the cultivar used. Because of the height of the plants, it was not possible to perform these measurements without damaging the new leaves. Therefore, it was noted weekly the appearance of unsheathed leaves (i.e. leaves that did not grow anymore), and the leaf area was calculated retrospectively at the end of the experiment from final leaf length and width measurements.

In addition, a 'collecting ratio' was used, defined as the ratio of the length of the leaf part that was directed towards the stem to the total leaf length, L. This 'collecting ratio' accounted for the leaf's ability to divert

DOI: 10.1002/hyp

Table I. Characterization of the experimental plots relating to vegetative (Ve), flowering (Fl), and bunch (Bu) stages. Incident rainfall, mean of the total throughfall and stemflow, and number of storms during the measurement periods[a]

Stage	Planting date	Regrowth cycle	Measurement period	Number of measurements	Dates of LAI measurements	Incident rainfall (mm)	Number of storms	Throughfall (mm)	Stemflow (mm)	Throughfall +Stemflow (mm)
Fl	Mar. 1999	1	26 Jul. 1999 to 12 Aug. 1999	10	28 Jul. 02 Aug. 05 Aug. 10 Aug.	164	39	116 [99, 133]	42 [34, 49]	158 [142, 173]
Bu	Nov. 1998	1	19 Aug. 1999 to 16 Sept. 1999	14	28 Aug. 2 Sept. 07 Sept. 10 Sept.	158	56	120 [91, 149]	38 [32, 44]	158 [130, 187]
Ve	Jul. 1997	4	7 Oct. 1999 to 29 Oct. 1999	11	11 Oct. 20 Oct. 26 Oct.	151	36	135 [116, 154]	27 [22, 31]	162 [144, 180]

[a] Confidence interval in parentheses.

water to the pseudostem and thus to contribute to the stemflow.

Rainfall partitioning calculation

To account for rainfall partitioning, stemflow and throughfall were expressed as the ratio of their respective volumes to the volume of incident rainfall calculated for a banana plant area (i.e. $2{\cdot}35 \times 2{\cdot}35$ m^2). According to the experimental design on Figure 2, the area covered by the bowls, i.e. the measurement area, was a little less than a quarter of the area devoted to each banana plant. The measurement area was large enough to integrate the local heterogeneities of throughfall. From there, the volume of throughfall for a banana plant was assessed from the total water volume of bowls multiplied by a factor of 4·18, which was the ratio of the surface occupied by each banana plant ($2{\cdot}35 \times 2{\cdot}35$ m^2) to the actual bowl surface ($25 \times 0{\cdot}23 \times 0{\cdot}23$ m^2).

Transmissivity calculations

Three combined variables were defined from gross transmissivity measurements: the radial transmissivity (T_R), the furrow transmissivity (T_F), and the interrow transmissivity (T_I).

One possible factor that can partly explain the variability of transmissivity is the distance from the pseudostem, considering an axial symmetry due to the plant morphology, with a crown formed of verticilated leaves inserted on the pseudostem with no ramification. Therefore a radial aggregation of transmissivities was chosen. The value for T_R was calculated for the 14 possible distances d between a bowl and the pseudostem (see Figure 2—in the present case there is no 15 possible d as expected because, given a bowl dimension of $0{\cdot}23 \times 0{\cdot}23$ m^2, bowls D1, C3, and A4 are at the same distance from the pseudostem). For each banana plant, T_R at a distance d was the average of the transmissivity ratios of the bowls situated at d from the pseudostem. For each crop stage and for each d, there was at least six replicates of T_R, one for each plant.

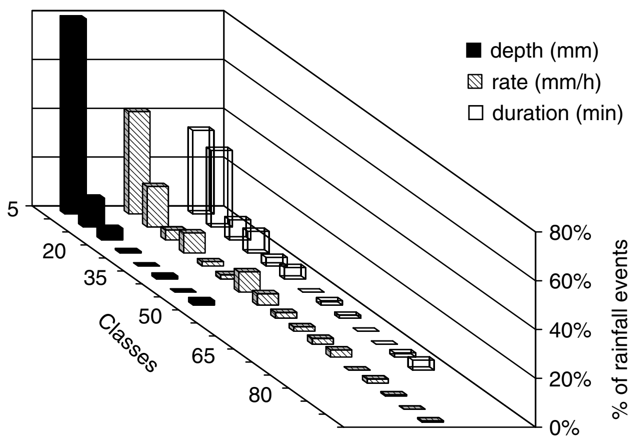

Figure 3. Distribution of rainfall events at 5 min steps throughout the experiment according to the total rainfall depth (in mm), rainfall rate (in mm h^{-1}), and rainfall duration (in min)

DOI: 10.1002/hyp

Thus the values for T_F and T_I from T_R were estimated. First the theoretical area of a banana plant was divided into a hundred cells of the size of a measurement bowl (Figure 2). Second, a theoretical transmissivity ratio for each cell was calculated; this theoretical transmissivity ratio was the mean T_R at d, with d equalling the distance between the cell and the pseudostem. Third, the cells were assigned to the furrow and to the interrow. Because the actual width of the furrow and the interrow were nearly the same, the same value was retained for both widths; for convenience this value was set at $5 \times 0{\cdot}23 = 1{\cdot}15$ m^2, which is the nearest multiple of the bowl dimensions from the actual value. Hence, the areas of the furrow and of the interrow were both equivalent to the area of 50 cells. Finally, T_F and T_I values were calculated: T_F was the average of the theoretical transmissivity ratio of cells in the furrow plus the stemflow; T_I was the average of the theoretical transmissivity ratio of cells in the interrow. Thus, a factor of 0·5 was assigned to the cells spanning the two compartments.

Runoff risk evaluation

The total surface runoff volume (SRV) was defined to account for surface runoff risks. SRV was the sum of the elementary surface runoff volume calculated for each 5-min steps, that is the amount $5/60 \times [T\,R_I - \mathrm{Inf}]$ (where $T = T_F$ or T_I according to the compartment involved in calculation; R_I is the intensity of incident rainfall in mm h^{-1}; Inf is the soil infiltration rate in mm h^{-1}; 5/60 is the interval in h). The reinfiltration processes of runoff water in a compartment were not considered.

A series of simulations were performed at the scales of plot, furrow and interrow, with different soil infiltration rates and different ages of banana. For the soil infiltration rate, three constant levels were chosen based on known saturated hydraulic conductivity corresponding to a high (100 mm h^{-1}), a normal (60 mm h^{-1}), and a low (30 mm h^{-1}) soil infiltration rate. These levels respectively characterized undisturbed soil, soil under intensive crop management practices, and soil affected by tillage in very bad conditions. It was assumed that the soil infiltration rates did not vary spatially and temporarily. For the age of banana at the beginning of the simulation, a 2-, 4- and 6-month-old crop was chosen, matching the three growth stages Ve, Fl, and Bu. The variation in leaf area during the simulation period was estimated from a logistic curve (see e.g. Brisson *et al.*, 1998), which was fitted on the experimental data.

The simulations were carried out during a period of 45 days, from 1 August 1999 to 14 September 1999 (Table II). This duration was a compromise between minimizing the effect of the changes in plant structure and considering enough rainfall events.

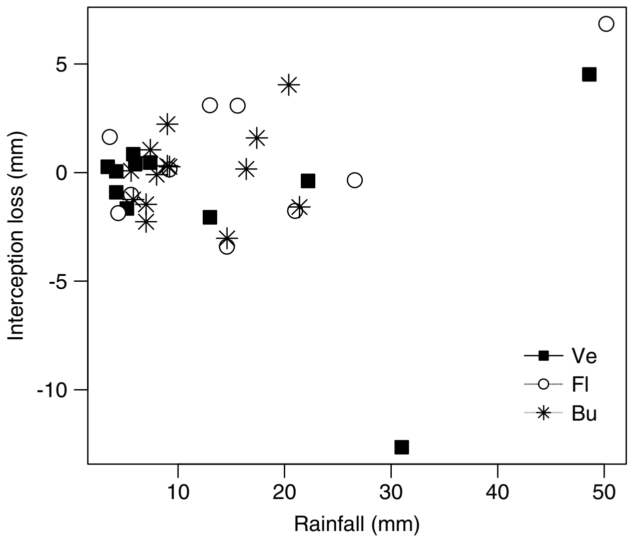

Figure 4. Relation between mean interception loss (in mm) and incident rainfall (in mm) at the plant scale for vegetative (Ve), flowering (Fl), and bunch (Bu) stages. The interception loss is assessed from the difference between the incident rainfall and the sum (stemflow + throughfall)

EXPERIMENTAL RESULTS

Rainfall partitioning

Table I shows rainfall partitioning for the three stages. The part of stemflow at the Ve stage was significantly lower than at the other stages; it represented 18% of the incident rainfall whereas for Fl and Bu stages it represented 26 and 24% of the incident rainfall, respectively. It was noticed that the sum of stemflow and throughfall (i.e. net precipitation) did not differ significantly from the incident rainfall. In line with this result, the average value of the interception loss—i.e. the difference between the incident rainfall and net precipitation, which mainly represents the canopy storage and the evaporation of the water stored in the canopy—did not differ significantly from zero [confidence interval (−0·74, 0·53)] for volumes

Table II. Characteristics of the rainfall regime during the simulation period

Period	Number of rainfall events	Rainfall volume (mm)	Classes[a] (mm h^{-1})	Number		Percentage	
				I_{max}[b]	I_e[c]	I_{max}	I_e
1 Aug. 1999	129	394	0–30	98	439	76	91
to			30–60	26	40	20	8
14 Sept. 1999			>60	5	5	4	1

[a] Classes = classes of rainfall intensity.
[b] I_{max} = maximum rainfall intensity on 5-min step per event.
[c] I_e = elementary rainfall intensity on 5-min step.

DOI: 10.1002/hyp

of incident rainfall less than 30 mm (see Figure 4). Moreover, the interception loss did not depend on the volume of incident rainfall (Figure 4). An interception loss close to zero is unusual and can be related to two points. First, the accuracy of the standard rainfall measurement 1 m above the soil should be questioned given that the top of the banana canopy that collected rainfall was 6 m above the soil. For this reason, especially in windy conditions, the incident rainfall could have been under evaluated. Second, interception loss should be weak because of a weak value of canopy storage and consequently of evaporation of the stored water. One reason comes from the assessment of the canopy storage: indeed, the high rainfall frequency that maintained the surface of the canopy wet during long periods and reduced evaporation prevented the canopy from storing additional water and thus minimized the canopy storage. A second reason is related to a weak volume of canopy storage because of the low wettability of the banana leaf surface. A weak interception loss would explain why no relation appeared between the interception loss and the volume of incident rainfall (Figure 4).

Radial throughfall transmissivities

Figure 5 shows that the transmissivities varied according to the distance from the pseudostem. For Ve and Fl, the area between 0 and 0·5 m from the pseudostem was better protected from incident rainfall. Actually, for these two stages, the comparison of the notched box plots according to McGill *et al.* (1978)—two medians differ statistically if the notches of the associated boxes do not overlap—showed that the median transmissivity on the area close to the stem was lower than elsewhere. On the contrary, for Bu stage, unexpectedly high transmissivities were observed on the area close to the stem. It was probably because some bowls collected a part of the stemflow, which left the pseudostem before the ring collector because of the inclined pattern of the pseudostem due to the bunch weight.

On the two ring areas more than 0·5 m from the pseudostem, i.e. (0.5 1] and (1 1.5], the median transmissivities decreased with the age of the crop: from 0·86 and 0·84 for the two ring areas of Ve to 0·47 and 0·45 for the two ring areas of Bu. This can be explained by the decrease in the number of drippings due to an increase in LAI from 1·9 to 3·24 for Ve and Bu, respectively. Also, the variability of transmissivity was greater and the maximum transmissivities were higher for Bu than for Ve. One possible reason is that the drippings collected water from larger leaf areas when the LAI increased.

Funnelling ratio

The FUN was evaluated from the slope of the relationship between stemflow and incident rainfall (Figure 6). Firstly, the stemflow per plant was roughly proportional to the incident rainfall. This result differs from that of (Levia, 2004) but is consistent with that of (Jiménez and Lhomme, 1994). This feature might be due to the low canopy storage of the banana plant previously discussed. Secondly, the older the crop age, the higher the FUN: FUN was 20 (standard deviation, SD = 1·3) for Ve and was 28 (SD = 1·3) for Fl and Bu. These differences can be explained by the variations in LAI and other traits of canopy architecture between stages.

The mean and the variability of FUN increased together with the LAI (Figure 7). This relationship was assessed by selecting the stemflow measurements, which were made within 1 day before or after each LAI recording. An explanation for the increase in FUN with LAI is that the last leaves were larger and remained more erect than the previous ones. Indeed, the increase in collecting ratio with leaf rank (order of emergence) accounted for this trend: the average collecting ratio was 0·3 for ranks 1 to 4 (the oldest leaves), 0·5 for ranks 5 to 8, and 0·9 for higher ranks; a collecting ratio of 1 was observed above the 14th leaf. Therefore, the higher the LAI, the higher the number of leaves with a high collecting ratio, and the higher the mean collecting ratio for the entire plant.

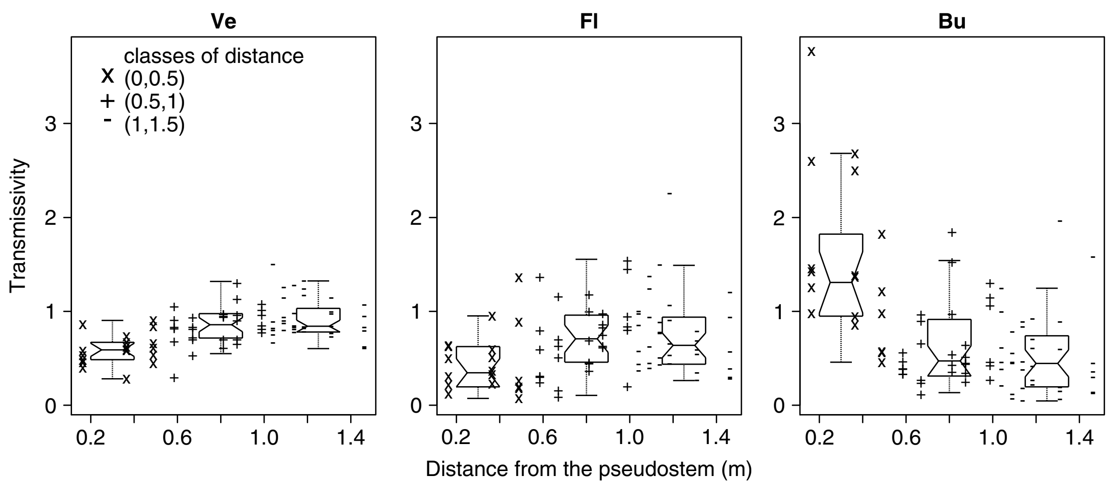

Figure 5. Variability of transmissivity according to the distance from the pseudostem for vegetative (Ve), flowering (Fl), and bunch (Bu) stages. The notched box plots represent the distribution of transmissivity according to three classes of distance from the pseudostem. The three horizontal lines of each box are the second quartile, the median, and the third quartile; vertical dotted bars accounted for 99% of the sample. Two medians differ statistically if the notches of the associated boxes do not overlap (McGill *et al.*, 1978)

DOI: 10.1002/hyp

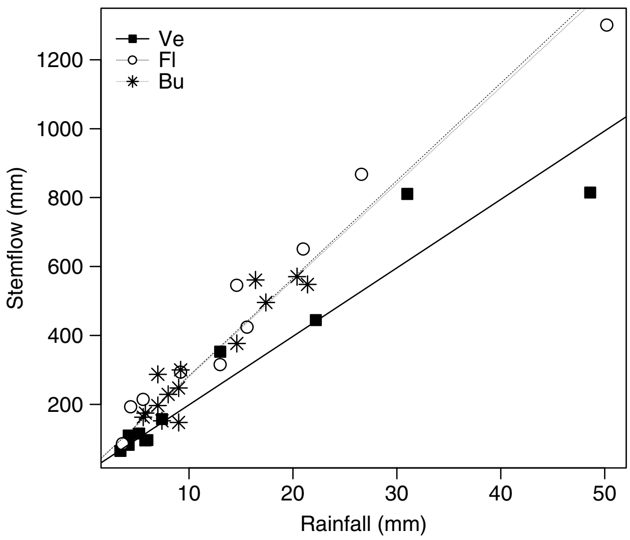

Figure 6. Variation in the measured stemflow with the incident rainfall for all the experiments for vegetative (Ve), flowering (Fl), and bunch (Bu) stages. The solid and dotted lines are the regression lines for each stage

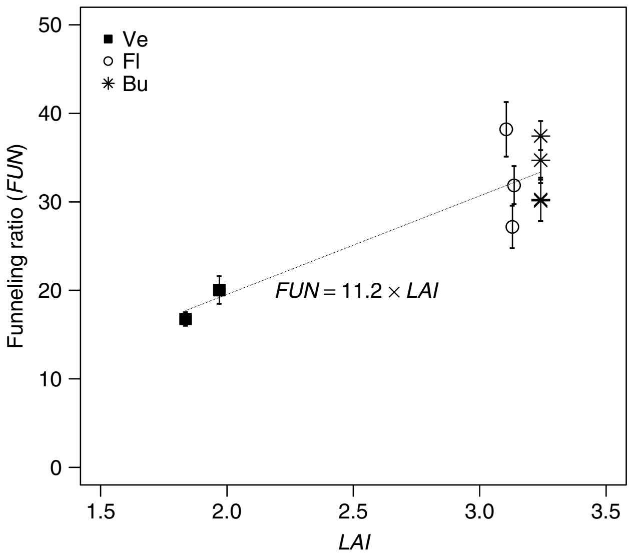

Figure 7. Variation of the funnelling ratio of the plants (FUN) with the LAI. Symbols represent the mean LAI of six plants and the vertical bars its variability; the line represents the least square regression

The larger variability of FUN for the higher LAI can be explained first by the increase in leaf shape heterogeneity, like tear due to wind and rain, and second by the bunch load effect. This larger variability was also consistent with results by (Crockford and Richardson, 1990), who showed that the stemflow varied with rainfall characteristics (intensity, duration, rainfall angle). A linear relationship (Equation (2)) was derived from the selected measurements of stemflow and for LAI values between 1·9 and 3·24:

$$\mathrm{FUN} = 11{\cdot}2\ \mathrm{LAI}; R^2 = 0{\cdot}76 \qquad (2)$$

Transmission coefficient on the furrow (T_F) and on the interrow (T_I)

The partitioning of water flows provided a higher transmissivity in the furrow, including stemflow, than in the interrow (Table III). According to the variation of T_R between Ve, Fl, and Bu (Figure 5), the difference between furrow and interrow increased with the age of the crop, from Ve to Bu.

To evaluate T_F throughout crop growth for runoff risk assessment, the investigation proceeded in two steps: first, the stemflow was estimated from Equation (2); second, a linear relationship was derived between T_F and LAI from the data (Equation (3)). Equation (4) expresses the conservation of the volume of water under the canopy and above the canopy. Then, T_I was estimated from Equation (5), which come from Equation (4).

$$T_F = 0{\cdot}11\ \mathrm{LAI} + 0{\cdot}99 \qquad (3)$$

$$R\ T_F L_F + R\ T_I L_I = (R - \mathrm{IL})(L_F + L_I) \qquad (4)$$

$$T_I = (L_F + L_I - T_F L_F)/L_I - \mathrm{IL}(L_F + L_I)/(R\ L_I) \qquad (5)$$

L_F and L_I were the width of the furrow and the interrow, R the volume of incident rainfall, and IL the interception loss (negligible here according to Figure 4).

RUNOFF SIMULATIONS

Presentation of the model

The effect of the spatial variation of transmissivity on surface runoff was assessed comparing a model with a homogeneous water distribution at the soil surface (single compartment model, 1M) to a double-compartment model (2M), accounting for the difference in transmissivity between the furrow and the interrow. Figure 8a shows the models represented by a schematic diagram plotting the variation of transmissivity T_F and T_I along a succession furrow/interrow. On the same scheme, the single compartment model (1M) is represented by a transmissivity of 1 on the same width as the width of the furrow/interrow succession (Figure 8b). It is assumed that the rainfall transmitted to the soil in a compartment was uniformly distributed before it infiltrated, so that surface runoff occurred as soon as the intensity of incident rainfall (R_I), multiplied by the appropriate transmissivity coefficient, was greater than the soil infiltration rate (Inf). Consequently, the runoff risk was evaluated from the comparison between the ratio Inf $/R_I$ and the transmissivity coefficients. According to Figure 8, four cases were possible:

Table III. Mean transmissivity ratios per compartment (T_F = furrow and T_I = interrow) and standard deviations (SD) for the three crop stages (Ve = vegetative, Fl = flowering, and Bu = bunch)

Stage	Furrow		Interrow	
	T_F	SD	T_I	SD
Ve	1·18	0·10	0·91	0·11
Fl	1·25	0·12	0·75	0·10
Bu	1·43	0·22	0·61	0·23

DOI: 10.1002/hyp

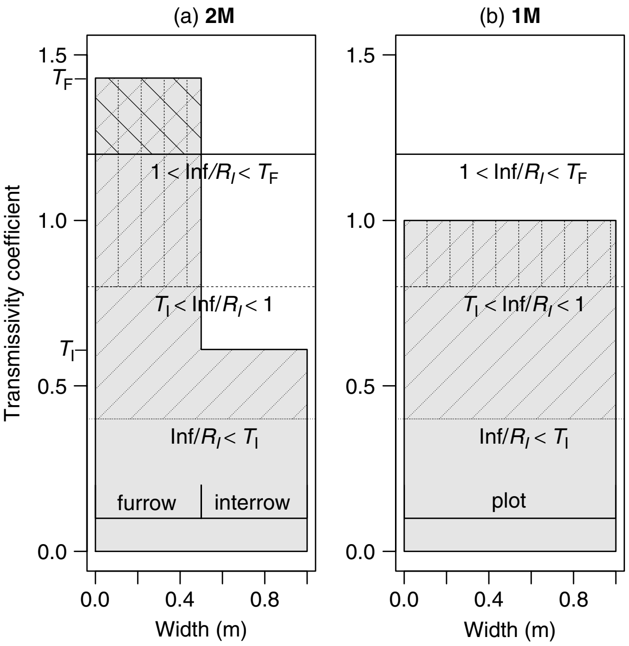

Figure 8. Schematic representation of the model used to account for spatial variation of transmissivity: (a) the double compartment model (2M) with different transmissivities in the furrow (T_F) and the interrow (T_I) (values presented here came from Bu stage measurements); (b) the single compartment model (1M) with a homogeneous transmissivity (T_B). Three levels of the ratio of soil infiltration (Inf) to intensity of incident rainfall (R_I) are represented by horizontal solid and dotted lines. The hatched areas represent levels of water excess that led to runoff

- *Case 1:* Inf/R_I < T_I: surface runoff occurred everywhere. The SRVs were proportional to the hatched areas, which were the same for 2M and 1M;
- *Case 2:* T_I < Inf/R_I < 1: surface runoff occurred for 1M and in the furrow for 2M. The SRVs were greater for 2M than for 1M.
- *Case 3:* 1 < Inf/R_I < T_F: surface runoff occurred only in the furrow for 2M.
- *Case 4:* T_F < Inf/R_I: there was no surface runoff.

Simulation results

First, at the plot scale, when Inf was smaller than 100 mm h^{-1}, rainfall partitioning at older stage (Fl and Bu) combined with furrowing increased the SRV relative to bare soil (Bs) (Table IV). This was due to the increased runoff in the furrow. There were no difference between Ve and Bs. Second, the absolute increase in SRV was at most +3% between Bs and Fl and Bs and Bu. This absolute increase was of the same order of magnitude for Inf of 30 and 60 mm h^{-1}. A higher increase in SRV was expected for Inf of 30 mm h^{-1}; this did not occur because the SRV in the furrow varied inversely as the SRV in the interrow (see case 1 described earlier), due to the lower transmissivity ratio in the interrow. However, the relative increases for Inf of 30 and 60 mm h^{-1} differed. When Inf was 30 mm h^{-1}, the absolute increase of +3% corresponded to weak relative increases of 0·7 and 2·1%, respectively, for Fl and Bu relative to Bs. In contrast, for Inf of 60 mm h^{-1}, the absolute increase of +3% corresponded to a relative increase of 300%. This was because surface runoff was observed only in the furrow (see case 2 described earlier). Finally, when Inf was higher than 100 mm h^{-1}, the rainfall pattern did not generate runoff.

Therefore, with the actual rainfall intensity pattern, when Inf is lower than 100 mm h^{-1} and with furrowing practice, simulations showed that rainfall partitioning led to an increase in surface runoff.

DISCUSSION

Hydraulic processes

That stemflow is an important element in the hydrology of banana plantations is consistent with results on Gramlnaceae like maize or sorghum (Parkin and Codling, 1990; Bui and Box, 1992). Higher stemflow rates were found in this study than those on plantain by Jiménez and Lhomme (1994), possibly due to the differences in LAI because of the lower plant density in their case. The proportion of rainfall that reached the soil as stemflow (18 to 26% in this study according to the stages) was two- to three-fold higher than that of Jiménez and Lhomme (1994) and of the same order of magnitude as that for similarly shaped plants (Parkin and Codling, 1990; Bui and Box, 1992; Bussière *et al.*, 2002). This proportion corresponded to a rainfall rate 20- to 28-fold higher at the plant collar, as showed by the FUN.

On average, the higher the LAI, the lower the mean transmissivity. However, some dripping points appeared in the middle of the interrow, providing locally high rainfall rates up to five-fold higher than the incident rainfall on the 529 cm^2 measurement area (i.e. bowl area). In any case, the spatial distribution of throughfall varied according to the distance from the pseudostem. For the Bu stage, the ring area more than 0·5 m from the pseudostem had the smallest median transmissivity. However, the bunch modified the water distribution: the area close to the pseudostem received high rainfall rates because of the bunch load effect. In contrast, for stages Ve and Fl, the area between the pseudostem and a distance of about 0·5 m from it was better protected from incident rainfall.

The simulations in this study showed that stemflow combined with furrowing increased the surface runoff

Table IV. Ratios (%) of surface runoff volume (SRV) to rainfall volume (394 mm for the simulation period) for the three crop stages (Ve = vegetative, Fl = flowering, and Bu = bunch) compared to bare soil (Bs) for different soil infiltration rates (Inf) (in mm h^{-1}) at plot, furrow (Fur.), and interrow (Int.) scale

Stages	Inf = 30			Inf = 60			Inf = 100		
	Plot	Fur.r	Int.	Plot	Fur.	Int.	Plot	Fur.	Int.
Bs	14	—	—	1	—	—	0	—	—
Ve	14	8	6	1	1	0	0	0	0
Fl	16	13	3	3	3	0	0	0	0
Bu	17	15	2	3	3	0	0	0	0

DOI: 10.1002/hyp

volumes relative to bare soil. The absolute increase was at most +3% of the incident rainfall volume. Although only few percentage points were recorded they represented large water volumes because of the tropical rains (e.g. 394 mm in 45 days during the period of simulation). The runoff rates from the simulation (on average, less than 3% of the rainfall volume for a soil infiltration of 60 mm h^{-1}) were lower than the runoff rate observed in the field (7% of the rainfall volume for a saturated hydraulic conductivity of 75 mm h^{-1}; Cattan *et al*., 2006) but both are of the same order of magnitude. These runoff rates accounted for soils with high infiltration characteristics.

Besides the effect of the spatial heterogeneity of water flows on runoff volumes, other effects may be encountered. The development of preferential drainage patterns (Paltineanu and Starr, 2000; Timlin *et al*., 2001) is doubtless one of the most important, especially because they may increase solute leaching.

Agronomic reflections

Obviously, the simulations in this study confirmed that the soil infiltration rate, affected by agricultural practices, was a major cause of runoff. Hence, intensive crop management practices and in particular soil tillage in wet conditions must be carefully evaluated. Mechanization remains a key factor in preventing runoff.

That runoff risk increases with the plant cover might seem paradoxical but similar results were found for soybean (Mac Isaac and Mitchell, 1992). For banana, this increase was mainly due to the plant architecture and to furrowing. However, the plant cover partly prevented soil particle detachment by direct raindrop impacts. However, it appears necessary to enhance soil protection in order to limit the adverse effect of runoff caused by stemflow. Managing crop residues in banana plantations is a possible solution after the first cycle because the leaves and stems of the previous cycle are left in the field. When crop residues are placed in the interrows, they increase soil surface protection and reduce runoff volume (Rishirumuhirwa, 1993; Khamsouk, 2000).

During plant growth, cultural practices should take into account the hydrological features depicted here. In particular, because the higher rainfall rates due to stemflow occurred near the stem, one should carefully consider the usual practice of spreading agrochemicals around the plant collar. All these results argue for reducing agrochemical application over time, and for the preferential location of agrochemicals in the protected areas (0 to 0·5 m from the pseudostem during vegetative growth) even over the entire surface if the application remains effective.

CONCLUSION

The present study confirmed that canopies like bananas, which exhibit high funnelling ratios, favour runoff, even on soils with a high infiltration rate like Andosol. This was due to the redistribution of the rainfall by the canopy, resulting in localized rainfall rates that exceed soil infiltration capacity. The main pathway for redistributed rainfall was stemflow, which diverted water at the plant collar. These features of banana plot hydrology have two main consequences. First, the spatial variations in rainfall rate and in soil surface relief must be considered together to account for water movement at the plot scale. In the present case, a simple double-compartment model allowed the authors to specify the runoff risk more accurately. Second, soil tillage practices and the localized application of agrochemicals must take rainfall distribution into account to reduce the surface runoff and the transport of solutes and solid particles.

Additional studies are needed to develop runoff/infiltration assessment models suitable for these rainfall regimes, especially in the case of heterogeneous canopies. Attention was mainly focused on the higher water fluxes due to the stemflow, but high rainfall rates were also observed below some dripping points, especially in old banana canopies. Further studies should evaluate the potential of those dripping points for runoff risks and soil detachment by splash.

ACKNOWLEDGEMENTS

This work was carried out with the joint financial support of the Guadeloupe Regional Council and the European Community as a support programme to sustainable banana cropping systems. The authors are grateful to G. Onapin and P. Artis for their technical contribution to the fieldwork. Thanks to R. Moussa for comments on the manuscript.

REFERENCES

Brisson N, *et al*. 1998. STICS: a generic model for the simulation of crops and their water and nitrogen balances. I. Theory and parameterization applied to wheat and corn. *Agronomie* **18**: 311–346.

Bui EN, Box JE Jr. 1992. Stemflow, rain throughfall, and erosion under canopies of corn and sorghum. *Soil Science Society of America Journal* **56**: 242–247.

Bussière F, Solmon F, Fouéré A. 2002. Implementation and evaluation of DROP, a model for the simulation of rainfall distribution below plants described in 3D. *Agronomie* **22**: 93–103.

Cattan P, Cabidoche Y-M, Lacas J-G, Voltz M. 2006. Effects of tillage and mulching on runoff under banana (Musa spp.) on a tropical Andosol. *Soil and Tillage research* **86**(1): 38–51.

Champion J. 1963. *In Le Bananier*. Maisonneuve and Larose: Paris; 263.

Crockford RH, Richardson DP. 1990. Partitioning of rainfall in a eucalypt forest and pine plantation in southeastern Australia: II. Stemflow and factors affecting stemflow in dry sclerophyll eucalypt forest and a Pinus radiata plantation. *Hydrological Processes* **4**: 145–155.

Crockford RH, Richardson DP. 2000. Partitioning of rainfall into throughfall, stemflow and interception: effect of forest type, ground cover and climate. *Hydrological Processes* **14**(16–17): 2903–2920.

Dorel M, Roger-Estrade J, Manichon H, Delvaux B. 2000. Porosity and soil water properties of Caribbean volcanic ash soils. *Soil Use and Management* **16**: 133–140.

FAO, 1990. *Soil Units of the Soil Map of the World.* FAO-UNESCO-ISRIC: Rome.

Herwitz SR. 1982. The redistribution of rainfall by tropical rainforest canopy tree species. In *First National Symposium on Forest Hydrology*, Inst. Aust. Eng. Publ., Melbourne; 26–29.

Herwitz SR. 1993. Stemflow influences on the formation of solution pipes in Bermuda eolianite. *Geomorphology* **6**: 253–277.

DOI: 10.1002/hyp

Jiménez OF, Lhomme JP. 1994. Rainfall interception and radiation regime in a plantain canopy. *Fruits* **49**(2): 133–139.

Khamsouk B. 2000. *Influence des systèmes de culture bananiers sur l'érosion, le bilan hydrique et les pertes en nutriments en Martinique (sol brun rouille a halloysite)*. PhD thesis, Montpellier; 180.

Levia DF. 2004. Differential winter stemflow generation under contrasting storm conditions in a southern New England broad-leaved deciduous forest. *Hydrological Processes* **18**(6): 1105–1112.

Levia J, Delphis F, Frost EE. 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. *Journal of Hydrology* **274**(1–4): 1–29.

Mac Isaac GF, Mitchell JK. 1992. Temporal variation in runoff and soil loss from simulated rainfall on corn and soybeans. *Transaction of the American Society of Agricultural Engineers* **35**(2): 465–472.

Manfroi OJ, *et al*. 2004. The stemflow of trees in a Bornean lowland tropical forest. *Hydrological Processes* **18**(13): 2455–2474.

McGill R, Tukey JW, Larsen WA. 1978. Variations of box plots. *The American Statistician* **32**: 12–16.

Navàr J. 1993. The causes of stemflow variation in three semi-arid growing species of northeastern Mexico. *Journal of Hydrology* **145**: 175–190.

ORSTOM, 1982. *In 3. La.Guadeloupe*. Atlas des départements français d'outremer. ORSTOM, CNRS.

Paltineanu IC, Starr JL. 2000. Preferential water flow through corn canopy and soil water dynamics across rows. *Soil Science Society of America Journal* **64**: 44–54.

Parkin TB, Codling EE. 1990. Rainfall distribution under a corn canopy: implications for managing agrochemicals. *Agronomic Journal* **82**: 1166–1169.

Perret S. 1992. *Etude de propriétés physiques, hydriques et mécaniques de sols andiques de la Réunion. facteurs naturels et anthropiques d'évolution des horizons culturaux, implications agronomiques et écologiques.* PhD thesis, ENSA Montpellier; 279.

Rishirumuhirwa T. 1993. Potentialities of the banana tree in the management and conservation of acid ferralitic soils in Burundi. *Cahiers ORSTOM* **28**(2): 367–383.

Timlin DJ, Heathman GC, Ahuja LR. 1992. Solute leaching in crop row vs interrow zones. *Soil Science Society of America Journal* **56**: 384–392.

Timlin DJ, Pachepsky Y, Reddy VR. 2001. Soil water dynamics in row and interrow positions in soybean (Glycine max L.). *Plant and Soil* **237**: 25–35.

2 Effects of tillage and mulching on runoff under banana (Musa spp.) on a tropical Andosol.

Available online at www.sciencedirect.com
SCIENCE DIRECT®

Soil & Tillage Research 86 (2006) 38–51

Soil & Tillage Research

www.elsevier.com/locate/still

Effects of tillage and mulching on runoff under banana (*Musa* spp.) on a tropical Andosol

P. Cattan [a,*], Y.-M. Cabidoche [b], J.-G. Lacas [c,d], M. Voltz [c]

[a] *CIRAD, FLHOR Department, Station de Neufchâteau, Sainte-Marie, 97130 Capesterre Belle Eau, France*
[b] *INRA, UR Agropédoclimatique de la Zone Caraïbe, Domaine Duclos, 97170 Petit-Bourg, France*
[c] *INRA, UMR LISAH, Bat. 24, 2 place Viala, 34060 Montpellier Cedex 1, France*
[d] *CEMAGREF, UR Qualité des Eaux et Prévention des Pollutions, 3 bis quai Chauveau, CP220, 69336 Lyon Cedex 9, France*

Received 13 May 2004; received in revised form 25 January 2005; accepted 3 February 2005

Abstract

This article assesses the extent of runoff in banana (*Musa* spp.) plantations on an Andosol of high water infiltration capacity (saturated hydraulic conductivity, K_{sat}, of over 60 mm/h) with high rainfall levels (2500–4500 mm of rain per year). This is an important issue, since the large quantities of inputs applied to banana plantations are likely to be displaced by runoff. Runoff was assessed over two crop cycles for two crop management strategies, viz. (1) tillage followed by furrowing and planting, and (2) planting in holes without prior tillage, with different soil cover management techniques for the second crop, viz. (1) mulching with harvest residues in every other interrow and (2) mulching with harvest residues in every interrow, whereas the soil was left bare for the first cycle. These strategies correspond to current practice among farmers. The results showed that runoff was generally moderate on the Andosol: runoff amounted to less than 55 mm in the first cycle with a total of 771 mm of rainfall, and about 70 mm in the second cycle, with a total of 1232 mm of rainfall. The mean runoff coefficients (RC) per rainfall event ranged from 5 to 11%. The differences in runoff between these two soil management strategies were particularly marked in the first cycle with no soil cover. Runoff was up to five times higher in the untilled plot (RC maximum value of 12%) for light rainfall events (less than 5 mm), notably due to the lower infiltration capacity of the soil (K_{sat} of 75 mm/h in the untilled plot to 265 mm/h in the tilled one) and despite the indirect hydraulic connectivity with the outlet, which increased the water residence time in the plot, compared to the tilled plot. The differences were reversed in cycle 2 for light rainfall events, where runoff in the tilled plot (RC maximum value of 8%) reached 10 times that in the untilled plot, as a result of mulching in the untilled plot, while in the tilled plot, the partially mulched soil reconsolidated. However, the runoff coefficient did not depend on the soil surface condition in the event of heavy rain (more than 10 mm), when runoff was widespread. Then, the maximum runoff coefficient per rainfall event never exceeded 34%. The results also showed that to compare strategies and soil management methods, it is crucial to analyse phenomena over successive crop cycles. In our case, this revealed that a low-mechanized strategy should not be ruled out, in view of the degree of runoff observed in the first cycle.

Keywords: Runoff; Andosol; Banana; Tillage; Mulching; Wheel tracks; Rainfall intensity

* Corresponding author. Tel.: +33 590 86 17 74; fax: +33 590 86 80 77.
E-mail address: philippe.cattan@cirad.fr (P. Cattan).

0167-1987/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2005.02.002

1. Introduction

Exported bananas (*Musa* spp.) are a major crop that currently covers nearly 1 Mha worldwide (Food and Agriculture Organization (FAO), 2002). The crop requires large quantities of inputs. Fertilizers and pesticides are responsible for serious water pollution observed in various places (St. Lucia: McDonald et al., 1999; Costa Rica: Castillo et al., 2000; Guadeloupe: Bonan and Prime, 2001). The fact that they are applied to the soil surface means that such products are likely to be removed rapidly by surface runoff, which is known to be one of the main causes of water pollution by pesticides in agricultural areas (Leonard, 1990). This article studies the extent and variation of surface runoff in banana plantations, according to the soil management strategies currently practised.

In the Caribbean, Central America, oceanic Asia and some parts of Africa, banana plantations are concentrated on young andic-type volcanic soils, which are characterized by substantial infiltration, a saturated hydraulic conductivity of over 60 mm/h (Perret, 1993; Dorel, 2000; Poulenard et al., 2001) and low runoff rates (Perret, 1993; Rishirumuhirwa, 1993; Dorel et al., 1996). In these conditions, runoff requires high-intensity rainfall. This is indeed the case on an Andosol planted with bananas, since they are almost always located in humid tropical climates. For example, the banana growing zone of Guadeloupe is situated on mountain slopes that receive an average of 2500–4500 mm of rain per year, with very high rainfall intensities: rainfall events with maximum intensities of over 30 mm/h, as measured over one minute, account for over 45% of the annual rainfall volume (Rossignol, 1990). Runoff may therefore occur, despite the high infiltration capacity of these soils.

Soil preparation and management techniques are known to affect the occurrence and intensity of runoff on a field scale. Many authors have observed their effect on the hydrodynamic characteristics of the soil surface (Richard et al., 1999), on its relief (roughness, surface detention), and consequently on runoff (Vansteelant et al., 1997): an increase in infiltration is seen immediately after tillage (Rao et al., 1998b); the creation of preferential water circulation and concentration zones follows cropping operations (Takken et al., 2001); a reduction in infiltration is found in wheel tracks (Hill, 1993; Basher and Ross, 2001). Such effects have already been demonstrated in the specific case of Andosols, in which the macroporosity of the topsoil is directly affected by tillage and compaction by wheeled vehicles (Dorel, 1993; Dorel et al., 1996), and on which frequent furrowing in line with the slope creates preferential water circulation pathways.

Minimizing runoff means not only controlling the effects of soil tillage, but also managing soil cover (e.g. Afyuni et al., 1997; Rao et al., 1998a,b; Mickelson et al., 2001). Banana is an annual crop that is grown over several cycles, from a single initial plant. Each plant is cut during the annual harvest, the vegetative part is left in the field and a new sucker grows at the base of the cut stem. After cutting, the residues (leaves and stems) are left in the field and placed in the interrows to increase soil surface detention and reduce runoff volume (Rishirumuhirwa, 1993; Khamsouk, 2000).

Our aim is to identify soil and soil cover management strategies capable of limiting runoff in banana plantations on a tropical Andosol. The studies of runoff in banana plantations quoted above observed the effect of various soil surface conditions as a result of agricultural practices, on a scale of a few m^2 and for single rainfall events. Their results varied largely because the soil and soil cover management strategies in banana plantations induce highly variable soil surface conditions in both time and space. It is therefore essential to analyse and quantify the dynamics of runoff over whole cropping cycles on a field scale in order to obtain a global picture of the influence of a given soil management strategy on runoff processes. In our study, we therefore analysed and compared runoff dynamics over two cropping cycles at the outlets of two plots managed with different initial soil preparation and different soil cover techniques commonly used in banana plantations. Since the two plots had the same soil and the same initial topographical features and had previously experienced the same agricultural practices, we assumed that the observed differences between the plots arose only from the difference in the soil management strategies applied. The results of our study provide a picture of how runoff occurs in fields (origin, pathways, flow rates, etc.) in relation to the main factors of variation identified, which are characteristic of the crop and its environment: rainfall, soil tillage and mulching.

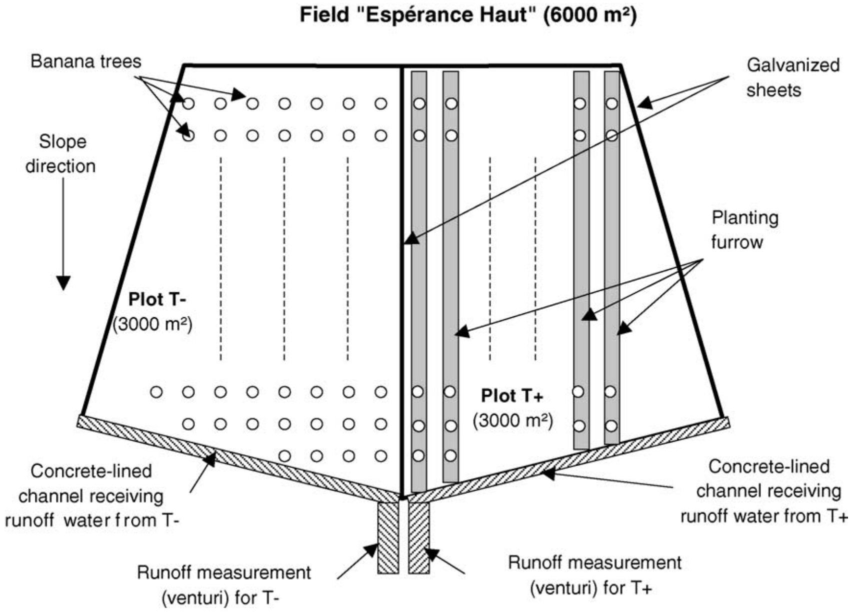

Fig. 1. Experimental layout in field "Espérance Haut" (6000 m^2).

2. Materials and methods

2.1. Study site

2.1.1. Climate and soil characteristics

The observations were made at the Neufchâteau experimental station (16°04′38″N, 61°36′04″W, 250 m), on the windward side of Basse Terre, Guadeloupe (FWI). Mean annual rainfall at the station is 3850 mm (Météo France, 1999). The field experiment was conducted at "Espérance-Haut" with a 6000 m^2 surface area and an average slope of 12%.

According to the detailed survey of the soils of the French West Indies (Colmet-Daage and Lagache, 1965), the soil there is an Umbric Andosol (FAO, 1990). Horizon A (0–30 cm), with a loamy texture, contains over 60 g kg^{-1} of carbon and has a medium-sized subangular polyhedral friable structure. The 1–3 cm diameter aggregates contain numerous tubular pores. The undisturbed horizon B (30–60 cm) has a fluffy texture typical of allophane soils, and a water content that never falls below 1000 g kg^{-1} under field conditions. Its light brown colour masks a carbon content of over 30 g kg^{-1}. It has a continuous macroscopic structure, with medium and fine tubular pores. Neither of the two horizons exhibits cracks at any time because the soil never dries out sufficiently due to the regularity of rainfall.

2.1.2. Experimental plot and management strategies

Field "Espérance-Haut" was divided into two plots separated by 50 cm wide galvanized sheets pushed vertically 20 cm into the ground (Fig. 1). The previous crop was banana, followed by 8-months fallow. Banana was planted in both plots on 21 February 2001. Different planting, soil preparation and soil cover strategies were adopted in the two plots (Table 1). In one, designated T+, a traditional mechanized technical sequence was adopted: (i) before planting, cross-ploughing with a disc plough, harrowing, and furrowing down the line of the slope (30 cm deep furrows, 2.35 m apart); (ii) planting of in vitro plantlets in the furrow, 2.35 m apart along the row; (iii) chemical weeding every two months; iv) after harvesting on 14 December 2001, spreading of banana plant residues in every other interrow. In the other plot, designated T−, a technical sequence with limited mechanical operations was adopted: (i) before planting, destruction of the fallow with glyphosate (*N*-(phosphonomethyl)glycine, $C_3H_8NO_5P$), plus one round with a rotary slasher to cut the grass; (ii)

Table 1
Crop planting strategy and soil surface conditions during the study period

	T+			T−	
	Crop establishment				
	Disc plough, harrowing			Weeding with glyphosate	
	Furrowing			Rotary slasher	
	Planting in furrow, 2.35 m × 2.35 m			Planting in holes, 2.35 m × 2.35 m	
Relief	Furrow	Interrow		Wheel tracks	Remaining plot
		Wheel tracks	Outside wheel tracks		
% Area	47	26	27	34	66
S.E. (%)	4	1	5	5	5
	Cycle 1	Cycle 2		Cycle 1	Cycle 2
Soil cover	Bare soil	Mulch every other interrow		Bare soil	Mulch every interrow
Study period	20 September–29 November 2001	14 December 2001–18 April 2002		20 September–29 November 2001	14 December 2001–18 April 2002
Dead cover (%)					
On 14 January 2002		43 (6)[a]			58 (6)
On 17 April 2002		32 (4)			56 (5)

[a] Standard error in brackets.

planting of in vitro plantlets in a square design (2.35 m × 2.35 m), in 10 cm diameter holes; (iii) chemical weeding every two months; iv) after harvesting on 29 November 2001, redistribution of plant residue in all the interrows on 14 December 2001. There was therefore a difference in the structure of the soil surface layers between the two plots. However, in addition, the soil surface conditions in each plot differed between the two cropping cycles. During the first crop cycle after planting, as a result of systematic weeding, the soil remained bare in both T+ and T−. Subsequently, during the second cycle, the soil in the two plots had a plant cover corresponding to the spreading of crop residues in every other interrow in T+ and in every interrow in T−. This led us to differentiate between our comparative analyses of runoff in the two plots for the first and second crop cycles.

2.2. Measurements

2.2.1. Rainfall and surface runoff

The runoff from each plot was channelled to the outlet via a concrete-lined channel at the lower end of the plot, and hence to a venturi channel (type E 1253 AZ, Hydrologic, Grenoble, France). The head of water in each venturi channel was measured using a bubble flowmeter (ALPHEE 3010, Hydrologic, Grenoble, France) adapted to the narrow width of the venturi, with 8 s time lapse. Rainfall volume and intensity were measured on site using a rain gauge (ARG100, Campbell Scientific, Shepshed, Leicestershire, UK) with a tipping bucket sensitive to 0.2 mm, with 1 min time lapse. The study period lasted from 21 September 2001 to 18 April 2002. Due to equipment breakdowns, the periods 2–15 November 2001, 21 February–14 March 2002 and 27 March 2002 from 9:00 am to midday were excluded from the analysis.

2.2.2. Soil topography

Soil surface condition and topography were characterized in each plot (Table 1). A topographical record was made with a theodolite (Trimble 3305 DR, INBC systèmes, Lyon, France), of the area between four banana plants. The data were interpolated by kriging to establish a digital terrain model on a square 0.3 m grid. The convexity perpendicular to the slope at a given node was estimated by the difference between its altitude and the average altitude of the two neighbouring nodes, divided by the distance between those nodes.

In plot T+, furrow and interrow widths were measured at 15 locations, and their relative area was deduced. The pathways taken by surface water in T+ were primarily the furrows and the wheel tracks in the interrows. The maximum lateral extent of these pathways therefore corresponded to the width of the furrows and of the wheel tracks. This was estimated over six transects crossing five consecutive interrows within the plot. In plot T−, the topography was not differentiated in the same way as in plot T+. Only the planting holes were distinguishable at the beginning of the first cycle, but they covered a negligible area. The extent of the water pathways in T− was almost exclusively linked to the tracks left by the wheels during rotary slashing. Their relative area was also estimated in six transects crossing five successive interrows.

2.2.3. Soil dead plant cover

Soil dead plant cover in the second crop cycle was estimated in T+ and T− by counting the existence/absence of dead plant matter every 10 cm along a 10 m horizontal line, in six replicates per plot (Table 1).

2.2.4. Determination of soil and water flow pathway hydraulic conductivity

The hydraulic conductivity of the topsoil was measured during the first crop cycle in different situations (outside wheel tracks in T+ and T−; in wheel tracks in T+ only, due to an equipment malfunction in T−), using a controlled-suction disc infiltrometer (TRIMS, Objectif K, Saint Avertin, France), which enabled characterization of the soil surface infiltration properties on a local scale (50 cm^2) at and near soil saturation. Infiltration was measured at matrix potentials of −10, −6, −3, and −1 cm of water, with three to five replicates per study zone. The results were processed using the method described by Reynolds and Elrick (1991), producing estimates of soil hydraulic conductivity at potentials of −10, −8, −4.5, −2, −0.5 and 0 cm of water. Furthermore, the saturated hydraulic conductivity of soil horizons A and B was determined by the constant-head permeameter method (Smith and Mullins, 1991), on undisturbed soil cylinders taken from four profiles dug in the field before soil preparation and planting.

2.3. Delimitation of rainfall events

To relate a rainfall event to the corresponding runoff generation, it was necessary to define both of them precisely. In this work, we defined a rainfall event as a rainy period in which there was never more than 15 min between two successive tips of the tipping bucket, and runoff generation as a period during which water flow was never interrupted for over 5 min. These choices were subsequently warranted by the clear correspondence in terms of both time and water volume of the associated flooding and rainfall events.

2.4. Statistical data analysis

To test the differences in runoff between the two plots, we tested the statistical differences in median values of runoff coefficients computed from the observed coefficients for each plot over sequences of rainfall events. This was done graphically using notched box plots (McGill et al., 1978); two medians were considered to differ statistically if the notches of the associated boxes did not overlap. The test compared the median runoff coefficients between the two plots and between cycles 1 and 2, which served to compare the four kinds of surface conditions described in Table 1. Moreover, to overcome the problem of differences in rainfall characteristics between cycles 1 and 2, the comparisons were made per rainfall amount class.

To test the differences in hydraulic conductivity between the various soil surface conditions, unpaired *t*-tests were performed.

3. Results and discussion

3.1. Spatial variation of surface runoff pathways and soil infiltration properties

Fig. 2 shows the connectivity between the concave zones in the two plots. In T+, the concave zones were either in the furrows or between the ridges resulting from furrowing in the interrow. Connectivity between the concave zones within the furrows or within the interrows was excellent, and was structured in line with the slope, due to the fact that the soil had been

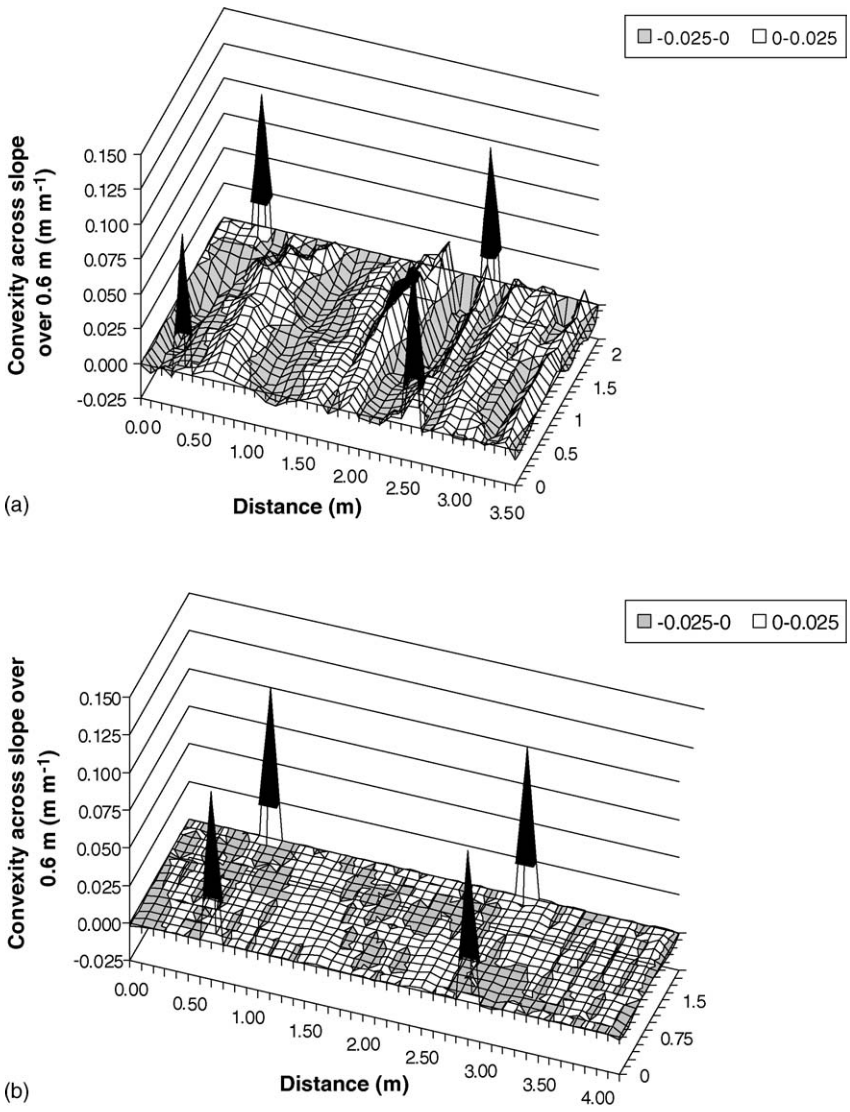

Fig. 2. Maps of relief convexity across the slope in (a) plot T+ and (b) plot T−. The vertical arrows represent the banana plants.

prepared by furrowing. In T−, the few existing concave zones were largely unconnected, which suggests that runoff was more tortuous in this plot than in T+.

Soil plant cover during the second cycle was assumed to be likely to modify the runoff characteristics analysed in the above paragraph. Table 1 shows that up to 60% of the soil in T− was covered by plants. The effect of this plant cover cannot be overlooked, particularly since it partially obstructed the runoff pathways and increased surface detention. Moreover, the sparser cover in T+ compared to T− (15–24% less in T+) and the difference in its spatial distribution were likely to be a source of variation in runoff amounts between the two plots.

Table 2 shows the high variability of the soil hydrodynamic properties observed in the two plots. This variability can be graded according to the variation in the soil surface conditions of the two plots. Firstly, as could be expected, conductivity values for

Table 2
Estimated hydraulic conductivity (mm/h) at different pressure values for different surface conditions in T+ and T−, as obtained from suction disc infiltrometer measurements

Pressure (cm H_2O)	T+ bare soil				T− bare soil	
	Wheel tracks		Outside wheel tracks		Outside wheel tracks	
	Mean	S.E.M.	Mean	S.E.M.	Mean	S.E.M.
−10	13	3.5	18	1.9	7*	1.9
−8	16	4.7	25	2.9	9*	2.4
−4.5	32*	6.1	56	5.5	19*	3.8
−2	68	6.8	100	11.8	42*	5.3
−0.5	138*	12.9	207	16.1	64*	6.5
0	171	18.1	265	30.7	75*	7.6

S.E.M.: standard error of the mean. Two comparisons were made by an unpaired *t*-test for each pressure value: (1) within-plot comparison: 'wheel tracks' vs. 'outside wheel tracks' for T+; (2) between-plot comparison: 'T+' vs. 'T− 'outside wheel tracks'. Means followed by asterisks (*) indicate significant differences at a 5% probability level.

the wheel tracks were lower than for the zones outside the tracks. Because of equipment malfunctioning, this difference could only be observed in T+, but it seems reasonable to assume that it also occurred in T−. Secondly, there was a significant difference in conductivity between the two plots: conductivity outside the wheel tracks in T+ was much higher than outside the wheel tracks in T−, and moreover, conductivity in the wheel tracks in T+ was similar to or even higher than conductivity outside the wheel tracks in T−. This clearly reflects the difference in soil preparation, which increased the porosity of the surface soil layer in T+. Hence T+, which had been tilled, exhibited higher conductivity values than T−. If we compare the mean saturated conductivity values of 135 mm/h measured for horizon A before this experiment and those observed for T− and T+ after planting the bananas, it emerges that the initial conductivity value is intermediate. This suggests that tillage had a positive effect on soil hydraulic conductivity, while planting operations had an adverse effect unless they were combined with tillage. The hydraulic conductivity measurements also showed a hydraulic discontinuity within the profile, with a saturated hydraulic conductivity value of 32 mm/h for horizon B. Lastly, it is clear that the conductivity values we measured were relatively high, even in wheel tracks, compared to those measured on other cultivated soils (e.g. Léonard and Andrieux, 1998; McGarry et al., 2000; Xu and Mermoud, 2001), which confirmed the high intrinsic permeability of the Andosol at our study site.

T+ was thus characterized by excellent connectivity in line with the slope and high hydraulic conductivity. T− was characterized by tortuous pathways and lower hydraulic conductivity.

Table 3
Characteristics of the two crop cycles with respect to rainfall and runoff and according to plot surface conditions

	Cycle	
	Cycle 1	Cycle 2
Period	20 September–29 November 2001	14 December 2001–18 April 2002
Number of rainfall events	285	577
Total rainfall, TR (mm)	771	1232
Mean maximum intensity (mm/h)	30 (33)[a]	18 (25)
Mean average intensity (mm/h)	19 (14)	13 (9)
Number of runoff events[b]	65	67
Total rainfall of runoff events (mm)	498	721

Surface conditions	T+ bare soil	T− bare soil	T+ mulch every other interrow	T− mulch every interrow
Runoff depth, RD (mm)	27	55	70	68
Global runoff coefficient, RD/TR (%)	3.5	7	5.5	5.5
Mean runoff coefficient per event (%)	5 (5)	11 (8)	8 (7)	7 (9)
Maximum runoff coefficient per event (%)	27	28	30	34

[a] Standard deviation in brackets.
[b] For which it was possible to determine a runoff volume.

3.2. Characteristics of rainfall data and initial conditions

During the $5\frac{1}{2}$-month measurement period, we recorded 2 m of rain. Rainfall volumes and the number of rainfall events were higher in cycle 2, while maximum intensity over a minute and mean intensity were lower (Table 3). This reflected the differences in the characteristics of rainfall events between the two cycles, as shown by rainfall distribution according to volume and maximum intensity classes (Fig. 3). Thus, cycle 2 was characterized by numerous rainfall events of low intensity – less than 48 mm/h – and fewer events with rainfall volumes of between 2 and 10 mm and intensities of over 72 mm/h. As a result, to interpret the effect of changes in soil cover between the first and second crop cycles, an analysis of each class of rainfall events is required, so as to take account of the variation in rainfall conditions between the two cycles. Lastly, it must be stressed that the water status of the two plots varied very little over time, as shown by monitoring the soil matrix potential, which consistently remained between 0 and −100 cm H_2O at a depth of 20 cm.

3.3. Determining factors of runoff initiation

Over the two cycles as a whole, only 15% of rainfall events resulted in runoff, which accounted for 61% of the total rainfall (Table 3). Fig. 4 shows that it was both maximum intensity and rainfall volume that determined runoff initiation. The classes for which the runoff frequency was over 75% represented 11% of the total number of rainfall events over the study period and 70% of the runoff events. Neither the planting strategy (soil tillage and planting technique) nor the spatial distribution of the mulch had any effect on initiating runoff: runoff invariably occurred in both plots for a given rainfall event. Moreover, installing a dead plant cover between the two cycles did not have any effect either, since the runoff frequencies for a given rainfall intensity and volume classes were similar in both cycles (not shown).

The values in Fig. 4 for the maximum rainfall intensity above which runoff was observed were sometimes lower than the surface saturated hydraulic conductivity values in T+ and T− (cf. Table 2). This may be due to concentrated water flow down the banana stem (Jimenez and Lhomme, 1994), due to the

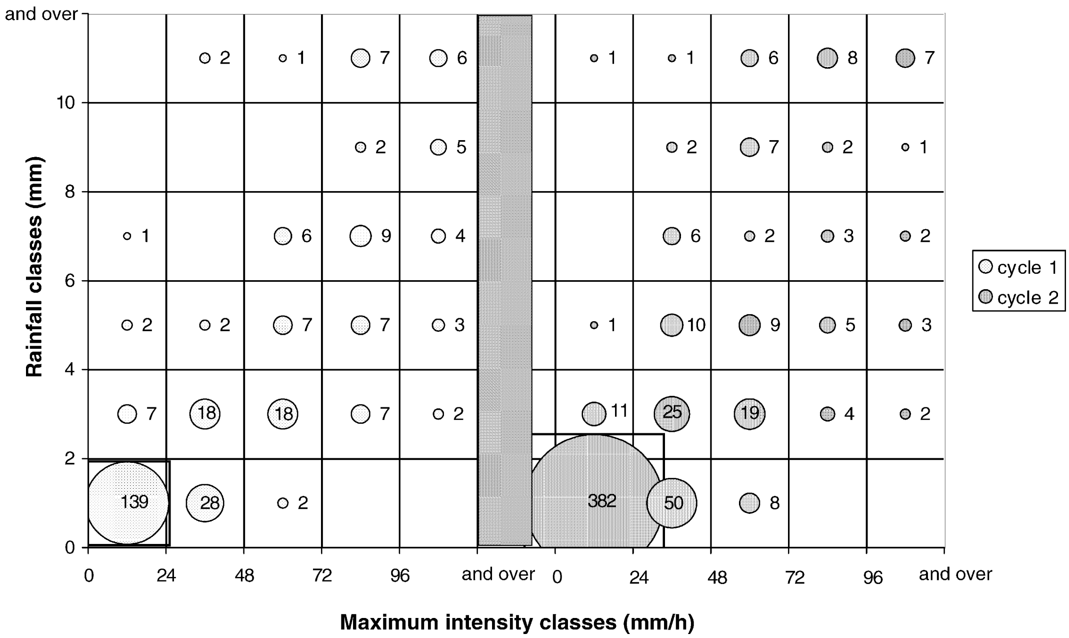

Fig. 3. Distribution of rainfall events according to rainfall volume and maximum rainfall intensity classes in cycles 1 and 2. Each circle corresponds to a class of rainfall volumes and intensities; its area is proportional to the number of rainfall events in the class, which is specified in the circle.

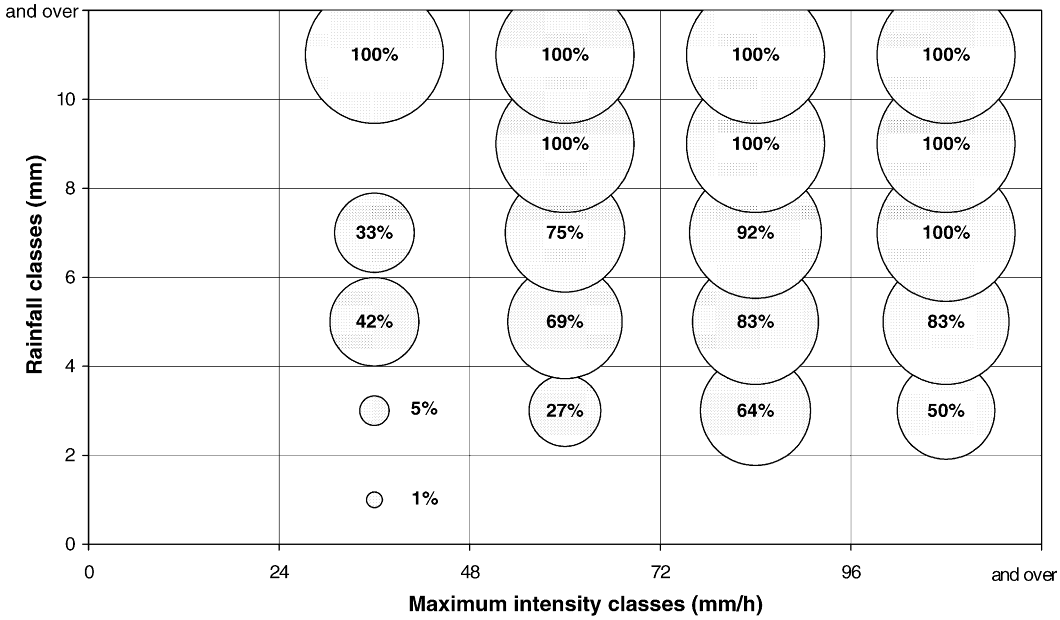

Fig. 4. Runoff frequency according to rainfall volume and maximum rainfall intensity classes over cycles 1 and 2. Each circle corresponds to a class of rainfall volumes and intensities; its area is proportional to the runoff frequency, which is given by the figure in the circle.

foliage concentrating the water. This phenomenon has also been observed with other types of land use (forest—Herwitz, 1993; *Sorghum diversicolor*—Bussière, in press). It can increase rainfall intensity 10-fold in some places. One other explanation could be that for many rainfall events, infiltration may have been controlled by horizon B, which was less infiltrable and was rapidly reached by the infiltration front.

3.4. Runoff variability

3.4.1. General characteristics

The overall runoff coefficient for the measurement period as a whole was under 7% (Table 3). The coefficients calculated per event did not exceed 34%. An analysis by rainfall volume class (Fig. 5) showed that runoff coefficients increased with rainfall volumes for both plots during cycles 1 and 2. This can primarily be related to the increase in maximum intensity for heavy rainfall events and the greater soil saturation during those events. Fig. 6 shows examples of runoff hydrographs induced by light and heavy rainfall events that were observed in T+ and T− during cycles 1 and 2. It shows that given the high rainfall intensity, even for light rainfall events, runoff was significant and occurred rapidly.

3.4.2. Effect of crop planting strategies

The combined effect of soil tillage and planting technique can be seen by comparing the two plots in cycle 1 when the soil in T+ and T− was still bare. This was done by analysing the variation in the runoff coefficient measured for single rainfall events, as defined in Section 2. As can be seen in Fig. 5, the median values for runoff coefficients were significantly higher in T− than in T+ for every rainfall amount class. If we now examine in Fig. 7 the variation in the ratio of runoff amounts in T+ to those in T− in cycle 1, we observe that, on average, the runoff volume in T+ was much lower than that in T− for small rainfall events but became increasingly similar to that in T− with increasing rainfall volumes. This phenomenon did not depend on rainfall intensity.

The lower runoff volumes in T+ in the event of light rainfall reflected the differences in the hydraulic conductivity of the main water pathways in the two plots, despite the better connectivity in line with the

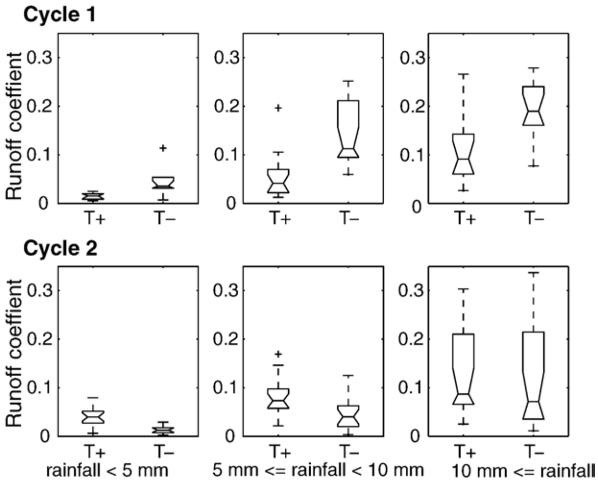

Fig. 5. Runoff coefficient distribution during cycles 1 and 2 per rainfall volume class in T+ and T− The difference between the median values is judged to be significant if the box plot notches do not overlap (McGill et al., 1978).

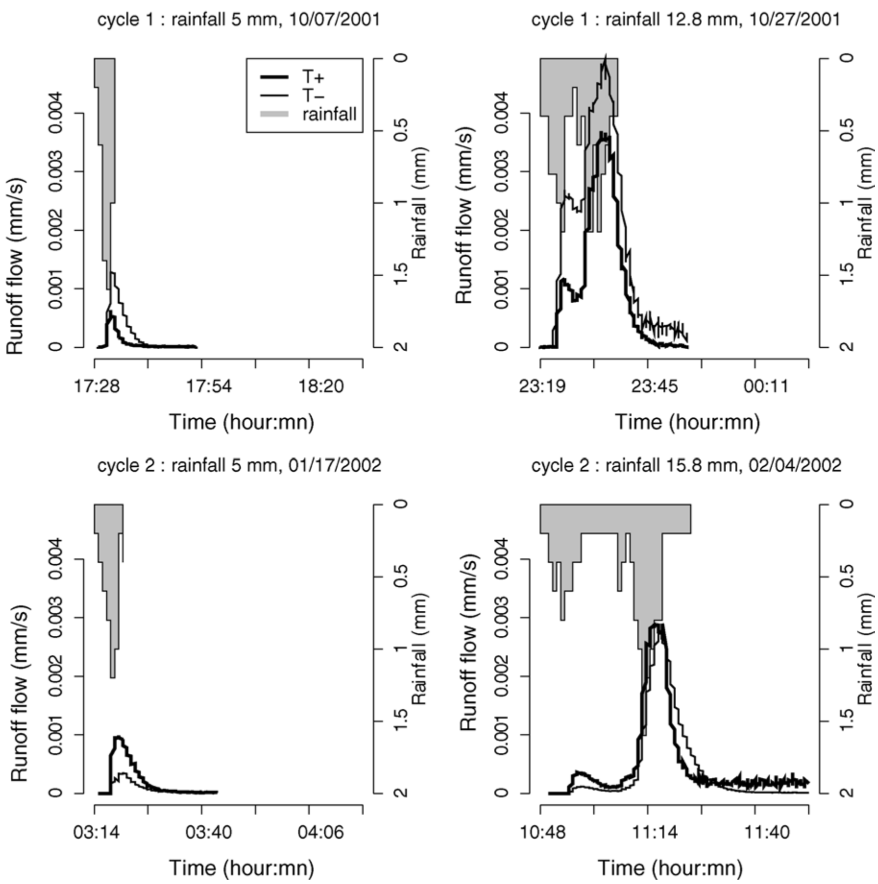

Fig. 6. Hydrographs of light (5 mm) and heavy (15 mm) representative rainfall during cycles 1 and 2 for T+ and T−.

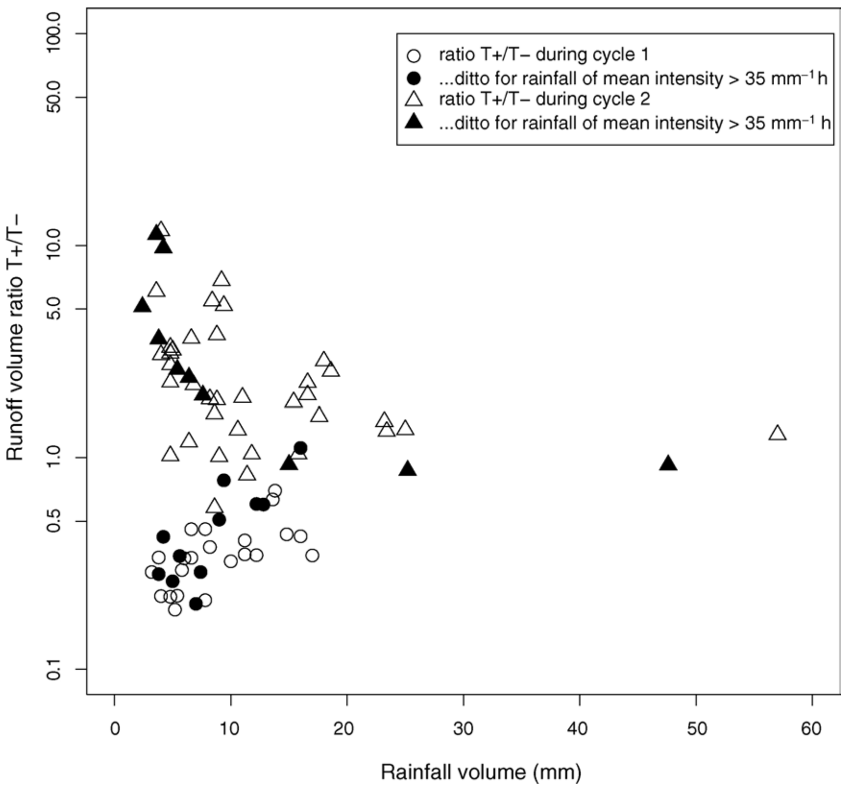

Fig. 7. Ratio of runoff volumes in T+ and T− as a function of rainfall volumes during cycles 1 and 2 for all rainfall events and for those with a mean intensity of over 35 mm/h.

slope on T+. However, the fact that for heavier rains T+ reacted in almost the same way as T− may be put down to two factors. One is that for heavy rainfall, the runoff contributing areas in T+ may have increased significantly and then extended, like in T−, to cover the whole plot. The other possible explanation is that in the event of large amounts of rain, the infiltration front may rapidly have reached horizon B in both plots, which therefore controlled the infiltration rate, and thereby the runoff rate.

3.4.3. *Comparison between bare soil and mulch in every interrow in the plot with limited mechanization*

To analyse this effect, we compared the runoff characteristics observed in T− with bare soil during cycle 1 and those with mulch during cycle 2. Fig. 5 shows that runoff coefficients in T− were lower on average in the second cycle than in the first, irrespective of the rainfall class. Since in the case of plot T− the infiltration properties can be assumed to remain stable from cycles 1 to 2, the reduction in runoff should be mainly related to the crop residue mulch applied to the interrows. In effect, a dead plant cover increases water residence times in a field, since the crop residue hinders water movements, slows down flow, creates retention zones and obstructs existing channels. This type of reduction in runoff rates as a result of mulching tallies with the observations by Rao et al. (1998b), working with rice straw mulch.

However, if we examine more closely the runoff coefficients for rainfall events of over 10 mm (Fig. 5) we observe that although there was a significant difference in runoff coefficients between bare soil and mulched soil (non-overlapping box plot notches), the maximum observed runoff coefficients were comparable. This suggests that in the event of heavy rain, sheet runoff may mask the effect of mulching as it masked the effect of crop planting strategies.

3.4.4. Comparison between bare soil and mulch in every other interrow in a traditionally mechanized field

The impact of mulching every other interrow only can be seen by comparing the runoff characteristics observed in T+ with bare soil during cycle 1 and those in T+ with mulched soil during cycle 2. Figs. 5 and 6 show that runoff coefficients in T+ for rainfall events of less than 10 mm were higher in cycle 2 than in cycle 1, and similar for rainfall events of above that threshold. Consequently, spreading crop residue in every other interrow of this plot was not proved to have any effect. In principle, mulching every other interrow should have reduced runoff, or at least resulted in the same degree of runoff, even if it had been ineffective. The reason for the increased runoff in cycle 2 may lie in the reduction in soil infiltration capacity in T+, as a consequence of gradual compaction of the tilled soil surface layer (Rao et al., 1998b) during cropping operations.

3.4.5. Change in runoff ratios between T+ and T− in cycle 2

Figs. 5 and 6 also show that unlike in cycle 1, runoff during cycle 2 was lower in T− than in T+, except for high rainfall volumes. The ratio of runoff volumes in T+ to those in T− varied in line with rainfall levels (Fig. 7): the runoff volume in T− was ten times lower than in T+ for light rains, which is no doubt related to the low runoff rates observed in T− for these small volumes of rainfall, for which mulching is most effective; the runoff volumes tended to be increasingly similar as rainfall volumes increased.

This inversion of runoff ratios between the two plots in the second cycle can be linked to the limiting effect of mulching on runoff in plot T− and the adverse effect of compaction in plot T+, as analysed above. Unlike in cycle 1, the differences between the two plots were less marked for heavy rainfall events, with the same maximum values.

4. Conclusion

In this study, a mechanized management sequence with prior soil tillage and furrowing was compared with one without soil preparation, over two crop cycles. In cycle 1, the former sequence was characterized by high soil infiltrability due to tillage and by the high hydraulic connectivity of topographical depressions with the outlet due to furrowing, whereas the hydraulic conductivity and connectivity were much lower in the latter. Additional differences between sequences appeared in cycle 2. Soil cover management was different, with crop residues applied in every other interrow in the tilled sequence and in every interrow in the non-tilled one.

The results showed that runoff was generally moderate on this Andosol, with mean runoff coefficients of 5–11% and always less than 34%, for a given rainfall event. However, this degree of runoff is sufficient to cause significant water contamination due to its flow intensity and to the solubility of the pesticides applied on the soil surface in banana plantations. The differences in runoff between the two soil management strategies were particularly noticeable if the soil was bare during the first crop cycle. They were primarily due to differences in soil infiltration properties. Against all expectations, furrowing appeared to have little impact on runoff, although it did increase hydraulic connectivity with the outlet. During the second crop cycle, the differences between the two crop strategies were reversed, due to the runoff limitation effect of generalized mulching under the non-tilled strategy and on the runoff-increasing effect of soil reconsolidation after tillage under the tilled strategy. Nevertheless, the differences between the strategies appeared to be less marked in the event of heavy rainfall, in which case runoff was widespread and was less affected by soil surface conditions.

The results showed that to compare soil management strategies, the relevant phenomena have to be observed over several crop cycles, taking into account all the changes in surface conditions that may occur. For example, in this study, if this had not been done, the conclusion of the study would have been different and the management strategy with prior tillage would have been advised for limiting surface runoff, since it performed better in this respect than the other strategy during the first crop cycle.

Acknowledgements

We are grateful to Alexis Champoiseau, Aymeric Simon and Germain Onapin for their contribution to this work. This study was funded by the Guadeloupe Region (FWI), the Ministère de l'Ecologie et du Développement Durable (France) and the European Community under the project "Assessment of water-pollution risks associated with agriculture in the French West Indies: management at the catchment scale".

References

Afyuni, M.M., Wagger, M.G., Leidy, R.B., 1997. Runoff of two sulfonylurea herbicides in relation to tillage system and rainfall intensity. J. Environ. Qual. 26, 1318–1326.

Basher, L.R., Ross, C.W., 2001. Role of wheel tracks in runoff generation and erosion under vegetable production on a clay loam soil at Pukekohe, New Zealand. Soil Till. Res. 62, 117–130.

Bonan, H., Prime, J.L., 2001. Rapport sur la présence de pesticides dans les eaux de consommation humaine en Guadeloupe. Rapport no. 2001-070. Ministère de l'Aménagement du Territoire et de l'Environnement, Ministère de l'Emploi et de la Solidarité, Paris, 77 pp.

Bussière, F., in press. Rainfall interception and water partitioning under sorghum (*Sorghum diversicolor*) and canavalia (*Canavalia ensiformis*) canopies. Eur. J. Agron., 12.

Castillo, L.E., Ruepert, C., Solis, E., 2000. Pesticide residues in the aquatic environment of banana plantation areas in the north Atlantic zone of Costa Rica. Environ. Toxicol. Chem. 8, 1942–1950.

Colmet-Daage, F., Lagache, P., 1965. Caractéristiques de quelques groupes de sols dérivés de roches volcaniques aux Antilles françaises. Cahiers de l'ORSTOM serie pédologie 8, 91–121.

Dorel, M., 1993. Travail du sol en bananeraies: cas des Andosols. Fruits 48, 77–82.

Dorel, M., Lafforgue, A., Bretaud, P., Le Breton, M., 1996. Etude de la contamination des eaux de ruissellement par les pesticides utilisés en bananeraie. Rapport d'exécution du Projet CORDET 93 D A 14, CIRAD-FLHOR, Guadeloupe, 27 pp.

Dorel, M., 2000. Effet des pratiques culturales sur les propriétés physiques des sols volcaniques de Guadeloupe et influence sur l'enracinement du bananier. Thèse de Docteur en Sciences Agronomiques et Ingénierie Biologique. Université catholique de Louvain, Belgique, 129 pp.

FAO, 1990. Soil Units of the Soil Map of the World. FAO-UNESCO-ISRIC, Roma.

FAO, 2002. Statistical Databases. Web site http://apps.fao.org.

Herwitz, S.R., 1993. Stemflow influences on the formation of solution pipes in Bermuda eolianite. Geomorphology 6, 253–277.

Hill, R.L., 1993. Tillage and wheel traffic effects on runoff and sediment losses from crop interrows. Soil Sci. Soc. Am. J. 57, 476–480.

Jimenez, O.F., Lhomme, J.P., 1994. Rainfall interception and radiation regime in a plantain canopy. Fruits 49 (2), 133–139.

Khamsouk, B., 2000. Influence des systèmes de culture bananiers sur l'érosion, le bilan hydrique et les pertes en nutriments en Martinique (sol brun rouille a halloysite). Thèse de Docteur en Science du Sol. ENSAM, Montpellier, 180 pp.

Leonard, R.A., 1990. Movement of pesticides in surface waters. In: Cheng, H.H. (Ed.), Pesticides in the Soil Environment: Processes, Impact and Modelling. Soil Science Society of America, Madison, WI, USA, pp. 303–350.

Léonard, J., Andrieux, P., 1998. Infiltration characteristics of soils in Mediterranean vineyards in southern France. Catena 32, 209–223.

McDonald, L., Jebellie, S.J., Madramootoo, C.A., Dodds, G.T., 1999. Pesticide mobility on a hillside soil in St. Lucia. Agric. Ecosyst. Environ. 72, 181–188.

McGarry, D., Bridge, B.J., Radford, B.J., 2000. Contrasting soil physical properties after zero and traditional tillage of an alluvial soil in the semi-arid subtropics. Soil Till. Res. 53, 105–115.

McGill, R., Tukey, J.W., Larsen, W.A., 1978. Variations of box plots. Am. Stat. 32, 12–16.

Météo France, 1999. Bulletin Climatologique Annuel 1999. Service Régional de Guadeloupe, Les Abymes, 23 pp.

Mickelson, S.K., Boyd, P., Baker, J.L., Ahmed, S.I., 2001. Tillage and herbicide incorporation effects on residue cover, runoff, erosion, and herbicide loss. Soil Till. Res. 60, 55–66.

Perret, S., 1993. Facteurs d'évolution des horizons culturaux, implications agronomiques et écologiques. Thèse de Doctorat en Sciences Agronomiques. ENSAM, Montpellier, France, 279 pp.

Poulenard, J., Podwojewski, P., Janeau, J.-L., Collinet, J., 2001. Runoff and soil erosion under rainfall simulation of Andisols from the Ecuadorian *Paramo*: effect of tillage and burning. Catena 45, 185–207.

Rao, K.P.C., Steenhuis, T.S., Cogle, A.L., Srinivasan, S.T., Yule, D.F., Smith, G.D., 1998a. Rainfall infiltration and runoff from an Alfisol in semi-aride tropical India. I. No-till systems. Soil Till. Res. 48, 51–59.

Rao, K.P.C., Steenhuis, T.S., Cogle, A.L., Srinivasan, S.T., Yule, D.F., Smith, G.D., 1998b. Rainfall infiltration and runoff from an Alfisol in semi-aride tropical India. II. Tilled systems. Soil Till. Res. 48, 61–69.

Reynolds, W.D., Elrick, D.E., 1991. Determination of hydraulic conductivity using a tension infiltrometer. Soil Sci. Soc. Am. J. 55 (3), 633–639.

Richard, G., Boizard, H., Roger-Estrade, J., Boiffin, J., Guérif, J., 1999. Field study of soil compaction due to traffic in northern France: pore space and morphological analysis of the compacted zones. Soil Till. Res. 51, 151–160.

Rishirumuhirwa, T., 1993. Potentiel du bananier dans la gestion et la conservation des sols ferrallitiques du Burundi. Cah. Orstom, sér Pédol. XXVIII (2), 367–383.

Rossignol, D., 1990. Les Régimes Pluviographiques de la Guadeloupe. IRD, Montpellier, France, p. 13.

Smith, K.A., Mullins, C.E., 1991. Soil Analysis: Physical Methods. Marcel Dekker, New York, 620 pp.

Takken, I., Govers, G., Jetten, V., Nachtergaele, J., Steegen, A., Poesen, J., 2001. Effects of tillage on runoff and erosion patterns. Soil Till. Res. 61, 55–60.

Vansteelant, J.Y., Trévisan, D., Perron, L., Dorioz, J.M., Roybin, D., 1997. Conditions d'apparition du ruissellement dans les cultures annuelles de la région lémanique. Relation avec le fonctionnement des exploitations agricoles. Agronomie 17, 65–82.

Xu, D., Mermoud, A., 2001. Topsoil properties as affected by tillage practices in north China. Soil Till. Res. 60, 11–19.

3 Spatial and temporal variations in percolation fluxes in a tropical Andosol influenced by banana cropping patterns.

Journal of Hydrology (2007) **335**, 157–169

available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/jhydrol

Spatial and temporal variations in percolation fluxes in a tropical Andosol influenced by banana cropping patterns

P. Cattan [a,*], M. Voltz [b], Y.-M. Cabidoche [c], J.-G. Lacas [b], J. Sansoulet [c]

[a] *CIRAD, UPR 26, Station de Neufchâteau, Sainte-Marie, 97130 Capesterre Belle Eau, FWI, Guadeloupe*
[b] *INRA, Laboratoire d'étude des Interactions Sol-Agrosystème-Hydrosystème (LISAH), UMR AgroM-INRA-IRD, Bat. 24, 2 place Viala, 34060 Montpellier cedex 1, France*
[c] *INRA, UR Agropédoclimatique de la Zone Caraïbe, Domaine Duclos, 97170 Petit-Bourg, FWI, Guadeloupe*

Received 3 April 2006; received in revised form 27 October 2006; accepted 20 November 2006

KEYWORDS
Percolation;
Rainfall partitioning;
Spatial variability;
Andosols;
Banana;
Lysimeters

Summary Spatial variability in percolation fluxes was studied in field plots cropped with banana plants, which induce very heterogeneous rainfall partitioning at the soil surface, with high subsequent infiltration in Andosols. Percolation fluxes were measured for just over a year at 1–7 day intervals in eight wick (WL) and gravity lysimeters (GL) that had been buried in the soil at a depth of 60 cm. The results revealed that WL captured unsaturated fluxes while GL only functioned after ponding occurred. The percolation flux measurements were highly biased with both systems, i.e. overpercolation with WL and underpercolation with GL. Percolation fluxes seemed, however, to be mainly unsaturated in the soil types studied. High percolation flux variability was noted on a plot scale, which could be explained by the vegetation structure: total percolation flux (WL) was 2.1-fold higher under banana plants; saturated percolation flux (GL) was 7-fold higher under banana plants and almost absent between banana plants. Eighty-eight per cent of the total variance in percolation flux could be explained by the rainfall intensity under the banana canopy, calculated while taking the rainfall partitioning by the vegetation and the initial water status into account. The number of lysimeters required for assessing percolation flux in a field plot can be reduced by taking the spatial patterns of the flux boundary conditions into account.

Introduction

Percolation fluxes in soil corresponding to the flow of water and solutes through the unsaturated zone of the soil are an

* Corresponding author. Tel.: +33 590 861 774; fax: +33 590 868 077.
E-mail address: philippe.cattan@cirad.fr (P. Cattan).

0022-1694/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2006.11.009

Nomenclature

BB	the site between banana plants
ET_0	potential evapotranspiration
EPP	elementary percolation period between two lysimeter readings
GL	gravity lysimeter
P	percolation volumes
R	rainfall volume
R_a	antecedent rainfall, or rainfall volume 48 h before the beginning of an EPP
UB	the site under a banana plant
WL	wick lysimeter

important factor of groundwater recharge and contamination by solutes. Its spatial and temporal variations have to be known especially in agricultural areas to improve the management of fertilizers and pesticides and limit their possible impact on soil and water resources. This is what this paper is concerned with in the case of banana crops where very large amounts of agrichemicals are used and in turn serious problems of water contamination have occurred (Bonan and Prime, 2001; Castillo et al., 2000).

The factors controlling the variability of percolation fluxes in soils are numerous. In essence, they all stem from the variability of the initial water status of the soil, of the soil hydraulic properties and the hydraulic boundary conditions. The influence of the variation of boundary conditions on percolation fluxes is certainly as important as that of the other factors. Microtopography and vegetation are main sources of the variations of boundary conditions. On one hand, microtopography acts by redistributing heterogeneously surface runoff when present (Augeard et al., 2005; Dunne et al., 1991; Gascuel-Odoux et al., 1991; Kirkby, 2002). In farmed fields, it is controlled by cropping practices. On the other hand, vegetation acts at two levels. First its root system exerts a suction on the soil, extracts water, which influences the soil water content and thereby the percolation fluxes in the soil. Second, its canopy intercepts rainfall, stores a part of it but also redistributes it between throughfall and stemflow, which, according to the crop and climate characteristics, can lead to a very heterogeneous pattern of boundary conditions at the soil surface. The heterogeneous redistribution of rainfall by canopies has been studied for a long time and is well documented for many types of canopies (Levia Jr. and Frost, 2003). However, the number of studies about its possible influence on the space-time variation of the soil water status and percolation fluxes is much more limited (Paltineanu and Starr, 2000; Starr and Timlin, 2004; Timlin et al., 1992; Van Wesenbeeck and Kachanoski, 1988). Moreover, to our knowledge, it has never been studied in the case of banana crops, despite the tremendous impact of this kind of canopy on the redistribution of rainfall (Bassette, 2005; Cattan et al., in press; Jimenez and Lhomme, 1994).

The measurement of percolation fluxes remains a challenge. The use of indirect methods to assess it is the most frequent. They are based on water balance calculations, and/or application of numerical modelling of water and solute flow, and require measurements of the evolution of soil water content and soil contamination and estimation of soil and crop properties. However, they are often very imprecise for monitoring the dynamics of water and solute fluxes, and especially for monitoring the peak flows of the percolation fluxes, which are known to be the most contaminating fluxes (Abbaspour et al., 2001; Magesan et al., 1995). Direct methods are still under development. They allow measuring continuously the fluxes of water and solutes *in situ*. Several devices exist; they are often referred to as lysimeters. They all intercept water by imposing a constant or variable water potential condition at a chosen soil depth. Their main weaknesses are related to the disturbance created when they are installed in the soil and to the possible differences in flow intensities and flow lines between the natural and sampled soil due to the imposed water potential condition. Among them, the zero-tension lysimeters (Boll et al., 1991; Goyne et al., 2000; Zhu et al., 2002) and the suction lysimeters (Boll et al., 1992; Brandi-Dohrn et al., 1996; Brye et al., 1999; Kosugi and Katsuyama, 2004) must be distinguished. The former sets the interface between the soil and the lysimeter at the atmospheric pressure and collects drainage water only when the soil above the interface becomes saturated. The latter applies at the soil–lysimeter interface a negative tension, set by a vacuum or by a hanging water column, which aims at reproducing as closely as possible the actual water potential gradient of the soil. A few studies only compared the efficiency of several types of lysimeter for collecting drainage water (Boll et al., 1991; van der Velde et al., 2005; Zhu et al., 2002). In these studies, zero-tension lysimeters collected always less water than the suction lysimeters, which can be explained by the differences in soil water potential gradient at the soil–lysimeter interface, but also by the divergence of fluxes created in the soil around the zero-tension lysimeter (Abdou and Flury, 2004; Boll et al., 1991) and by the convergence of flow in the suction lysimeter (van der Velde et al., 2005) when the imposed negative pressure was smaller on average than the soil water potential. Another difference between both lysimeters is the origin of the collected waterflow. Several authors (Boll et al., 1992; Holder et al., 1991; Landon et al., 1999), referring to the dual porosity concept, suggest that zero-tension lysimeters collect essentially macropore flow whereas the suction lysimeters also collect matrix flow. Wenner et al., 1991, provide an experimental confirmation of it by analyzing $\delta^{18}O$ of percolation waters from zero-tension and suction lysimeters. It seems therefore possible to study the proportions of the so-called macropore and matrix flows by comparing drainage fluxes of different types of lysimeters (Hangen et al., 2005; Landon et al., 1999).

The main objective of this paper was to analyze the specific influence of the banana cropping structure and canopy on the spatial and temporal variation of percolation fluxes on a volcanic Andosol with high draining properties at the field scale under humid tropical conditions in Guadeloupe (French West Indies). A secondary objective was to compare zero-tension and suction lysimeters for estimating the spatial variation of macropore and matrix flow in Andosols, which may exhibit preferential flow patterns given the hydrophobic nature of their constituents (Clothier et al., 2000; Poulenard et al., 2004). The experiment used a set of zero-tension and suction lysimeters located under and between the banana plants for monitoring drainage fluxes over two consecutive cropping cycles in 2001 and 2002.

Materials and methods

Experimental site

The study was conducted at the Neufchâteau research station (16°04′38″N, 61°36′04″W, 250 m), on the windward side of Basse Terre, Guadeloupe. Mean annual rainfall at the research station is 3850 mm (Météo-France, 1999). The field experiment was located at the field site ''Espérance-Haut'', with a 6000 m^2 surface area and a mean slope of 12%. The previous crop was banana, followed by 8 months of fallow. Banana was planted on 21 February 2001 in a square block design (2.35 × 2.35 m; 1800 plants ha^{-1}).

According to a detailed survey of the soils of the French West Indies (Colmet-Daage and Lagache, 1965), the soil type is an umbric Andosol (FAO, 1990). Horizon A (0–30 cm; soil bulk density 0.71; particle density 2.44; pore volumes 71%), with a loamy texture, contains over 60 g kg^{-1} of carbon and has a medium-sized subangular polyhedral friable structure. The 1- to 3-cm diameter aggregates contain numerous tubular pores. The undisturbed B horizon (30–60 cm; soil bulk density 0.49; particle density 2.59; pore volumes 81%) has a fluffy texture typical of allophane soils, and a water content that never falls below 1000 g kg^{-1} (volumetric water content of 49%) under field conditions. Its light brown colour masks a carbon content of over 30 g kg^{-1}. It has a continuous macroscopic structure, with medium and fine tubular pores. The saturated hydraulic conductivities of horizons A and B were 135 and 32 mm h^{-1}, respectively (Cattan et al., 2006). We found no evidence of a water table nearby the soil surface during the excavation of the soil pits. Moreover, the deepest tensiometric measurements did not show any water table throughout the monitoring periods. Finally, a gap of more than 20 m between the field and the river below, suggested the water table was far below the soil surface.

Measurements and calculations

Climatic variables

Incident rainfall and rainfall partitioning by plant canopy. Incident rainfall (R) was measured on site using a rain gauge (ARG100, Campbell Scientific, Shepshed, Leicestershire, UK) with a tipping bucket having a measurement resolution of 0.2 mm.

Rainfall interception by the banana plant canopy results in a heterogeneous rainfall partitioning on the soil. Our previous results (Cattan et al., in press), which concerned the impact of rainfall partitioning by banana on surface runoff generation, showed that stemflow transports 24% of the rainfall to the soil, while 76% drips through the canopy. The resulting amounts of rainfall reaching the ground were evaluated on the basis of the following assumptions:

(i) under banana plants, total stemflow per plant is uniformly partitioned over a surface area surrounding each banana plant, named S_{UB} , supposed equal to 0.5625 m^2 which is the surface area of the lysimeters described later;
(ii) between banana plants, the volume of water dripping through the canopy is uniformly partitioned over a surface area, named S_{BB}, taken equal to 4.96 m^2, which is the complementary of S_{UB} to the elementary area per banana plant, named S, amounting to 5.5225 m^2, i.e. the area of the banana planting grid (2.35 m × 2.35 m) (Fig. 1).

Let us define the rainfall partitioning coefficients per plant, C_{UB} and C_{BB}, as the ratios of the observed rainfall amounts reaching the soil – respectively under the banana plants over S_{UB} and between the banana plants over S_{BB} – to the rainfall amounts observed above the canopy. The ratios C_{UB} and C_{BB} are estimated by:

$$C_{UB} = [(0.24 \times R^{*}5.5225)/0.5625]/R = 2.36$$
$$C_{BB} = [(0.76 \times R^{*}5.5225)/(4.96)]/R = 0.85$$

with R expressed in mm.

Consequently, the ratio between the rainfall volumes reaching the soil under the banana plants and between the banana plants is of 2.8 (2.36/0.85), which will be compared later in the paper with the ratio of percolation volumes under and between the banana plants.

Reference evapotranspiration (ET_0), crop evapotranspiration under standard (ET_c) and non-standard conditions ($ET_{c\,adj}$). ET_0 was calculated by its previously determined relationship with global radiation in Guadeloupe (Bastergue,

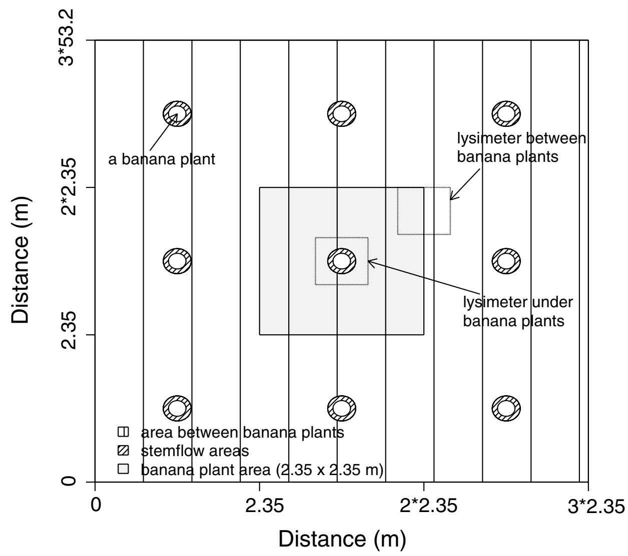

Figure 1 Schematic diagram showing the position of the lysimeters in the banana field relative to the areas between banana plants and to the area receiving stemflow.

1988). ET_c is the product of ET_0 and the crop coefficient K_c; ET_c can be assimilated to ET_0 because K_c for banana are close to unity (0.8—1.1) when the canopy is fully developed. Over the monitoring period, since measurements started after flowering, the banana canopy exhibited almost always a maximal leaf area (leaf area index of 3.3), the canopy from one banana plant overlapping with the adjacent plants. Only for two months, following harvesting, leaf area index decreased somewhat until suckers reached their full development. On this basis, we considered that ET_c over the monitoring period could be approximated by ET_0 and, given the non-limiting water supply conditions at the Neufchâteau station, we also assumed it was also the case for $ET_{c\,adj}$.

Lysimetry

The lysimeters used consisted of a 75 × 75 cm galvanised iron plate (Fig. 2), containing three 20 × 20 cm compartments located in the middle of the main plate and designed to collect water via fibreglass wicks within a standard water potential range of 0—5 kPa. The rest of the plate served as a gravity lysimeter designed to collect percolated water samples within a null to positive water potential range. A hole was drilled in each compartment to channel the sampled water to underlying collection chambers. This system enabled sampling of water fluxes in the zones covering the fertiliser/pesticide application zone (25 cm radius around the banana pseudostems) and accounting for a major part of the heterogeneity between banana plants. The fibreglass wicks were 1.45 cm diameter (1/2″ diameter round fibreglass, Pepperell Braiding Company, Massachussets, USA) with a Ksat of 11,680 mm h^{-1}. The sampler size was determined using the method described by Knutson and Selker (Knutson and Selker, 1994). The saturated hydraulic conductivity of the soil was estimated with a controlled-suction permeameter (TRIMS, Objectif K, Saint Avertin, France), and the measurements were processed using the method described by Reynolds and Elrick (Reynolds and Elrick, 1991). Finally, two 50-cm long wicks were implanted in each compartment. The wicks were unbraided, frayed, and spread across on soil aggregates scattered on the surface of each compartment to ensure contact with the soil overlying the sampler. In the field, when the banana plants were present, we dug trenches beside banana plant. Then, we dug two excavations horizontally at 60 cm in depth in the B horizon, one from the edge of the trench towards the banana plant and the other from the upstream edge of the trench. The lysimeters were inserted in the excavations and the wick surfaces were raised into contact with the soil above using two car jacks. Finally, the lysimeters were wedged with wooden blocks and the trench was backfilled with the excavated material. The root density is very small at 60 cm in depth and is maximum near the surface at the base of banana plants (Gousseland, 1983).

Tensiometry and soil moisture indicator

The soil moisture potential was measured by tensiometry at three depths (10, 30, 50 cm). A soil moisture indicator was determined by comparing the tensiometric measurements with cumulated rainfall amounts measured at different time steps prior to the moisture potential measurements. We noted that the cumulated rainfall amount 48 h before the moisture potential measurements revealed the mean soil moisture potential dispersion, especially under near-saturation conditions (around − 25 cm water) (Fig. 3). The 48-h cumulated rainfall amount was thus used as a soil moisture indicator.

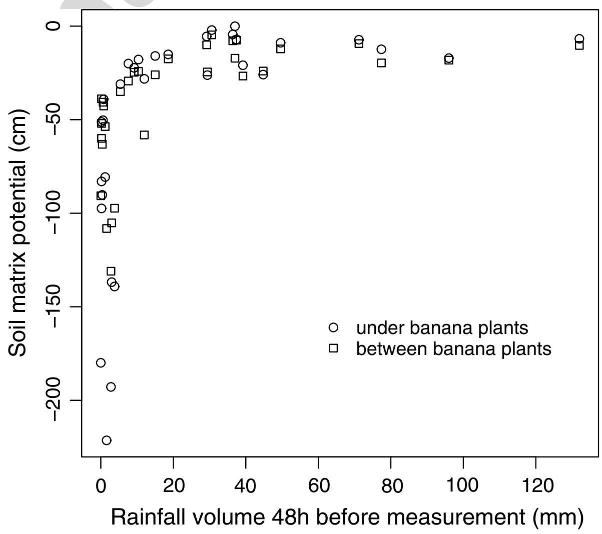

Figure 3 Relation between the soil matrix potential and the total rainfall 48 h before measurement.

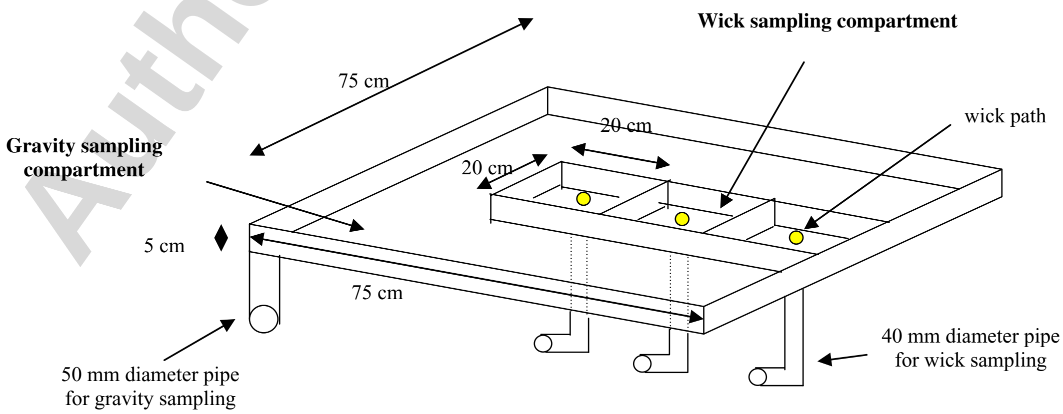

Figure 2 Schematic diagram of a lysimeter for wick and gravity sampling.

Water balance

The simplified water balance components were calculated as follows. The mean percolation per plot was estimated as a weighted average of the volumes percolated under the banana plants (P_{UB}) and between plants (P_{BB}) according to the term on the left side of Eq. (1) given below. Given the length of summation period, the variation in supply (dW) can be considered as negligible relative to the rainfall volumes (R) and thus would have little influence on the water balance. Runoff (r) was evaluated on average at 5% of the incident rainfall by Cattan et al. (2006); S, S_{UB} and S_{BB} are the previously described surface areas.

$$(S_{UB}/S)P_{UB} + (S_{BB}/S)P_{BB} = R - r - ET_0 + dW \tag{1}$$

with $S_{UB}S_{BB}$ and S in m^2; P_{UB}, P_{BB}, R, r, ET_0 and dW in mm.

Sampling design

Monitoring sites

To account for the heterogeneity in the rainfall distribution in the banana plantation, spatial variations in soil infiltration due to agricultural practices (tillage, planting techniques, etc.) and the heterogeneity in the distribution of fertiliser and pesticide applications, two different sampling sites were selected: the base of banana plants and the space between banana plants. The base of banana plants is an area where rainfall accumulates after stemflow, and it is also where fertilisers and pesticides are mostly applied. The area between banana plants is generally protected by the canopy from incident rainfall. In this area there are many factors responsible for the heterogeneity of soil surface: depressions and mounds in the soil after tillage, machinery wheel tracks, dead and live vegetation cover.

Based on these factors, for percolation measurement, the experimental setup included eight lysimeters installed at four locations on the plot, with one sampler installed under a banana plant and another installed between plants at each location. For soil water potential monitoring, 4 sets of three tensiometers at three depths (10, 30, 50 cm) were located on two locations apart from the lysimeter sites, one close to the pseudostem of a banana plant and another between banana plants.

Monitoring period

The monitoring period was from 10 September 2001 to 18 December 2002. The period from 14 December 2001 to 20 February 2002 was excluded from the analysis due to disturbances at the test sites induced by the first-cycle banana harvest. We obtained a total of 184 lysimetric measurements corresponding to the same number of elementary percolation periods (EPP), with the duration determined by the frequency of the sampler readings (generally three times a week). The frequency was increased during certain periods in order to more closely monitor and measure pollutant concentrations in the percolation waters. However, the frequency was decreased during periods without rainfall. The duration of 92% of the EPP was less than 3 days. The tensiometers were read weekly from 19 February to 15 May 2002.

Results

General climatic and percolation flux characteristics

Fig. 4 shows a heavy rainfall regime with rain almost every week (median volume 67 mm/week). There were however periods of relatively small rainfall in November 2001 and from mid-May to mid-July 2002. ET_0 was almost always lower than the precipitation amount. Percolation on the field plots was thus always positive, as indicated by the wick sampler measurements. The percolation volumes recorded over the time course of the study were heterogeneous, however, with marked differences depending on the type of sampler used and/or its location.

Preliminary comparison of fluxes recorded in wick and gravity lysimeters

The mean WL percolation volume per plot was much higher than that recorded for GL (Table 1), which is consistent with results reported elsewhere (Boll et al., 1991). Overpercolation was noted in WL and underpercolation in GL, and the volumetric percolation recorded with these two types of sampler amounted to 220% and 13%, respectively, of the volume estimated via the water balance (Eq. 1). This can be explained by suction lysimeter induced lateral heterogeneity in the soil water potentials resulting in percolation flux convergence in the soil layer over WL (Holder et al., 1991) and flux divergence over GL (Brandi-Dohrn et al., 1996). The overpercolation in WL can also be explained by the possibility that the mesh samplers were of unsuitable size, as mentioned by various authors (Knutson and Selker, 1994; Lacas et al., 2004). Overall, these biases of both lysimeters imply that their observed fluxes should be considered in relative terms and correspond to lower and upper boundaries of the actual percolation fluxes.

The impact of the initial water conditions on percolation flux onset and on the percolated volume differed for GL and WL. This was demonstrated for UB sites for which substantial percolation fluxes could be observed in GL and WL (Fig. 5). For GL (Fig. 5a), the initial water conditions, as represented by R_a, did not have a clear effect on percolation flux. During the EPPs, rainfall above a threshold between 10 and 20 mm was required to be able to record the percolation flux in GL. This supports the hypothesis that gravity lysimeters only recover fluxes after ponding occurs at the soil interface. Conversely, for WL (Fig. 5b), the initial water conditions had a clear impact on the percolated volume; for a given rainfall percolation, flux was higher when the initial conditions were humid. Percolation also occurred in WL when it did not rain during EPP, which can be explained by the fact that wick samplers collect unsaturated percolation fluxes. Under bananas, the percolation flux regression line in WL, according to the rainfall amounts, accounted for 83% of the variance, while 89% of the variance was accounted for when R_a was introduced as an additional variable (the differences in fit between the two models — with or without R_a — is significant at the level of $1^0/_{00}$). When comparing volumes percolated in WL and GL over the EPPs (Fig. 6), percolation volumes in WL were clearly

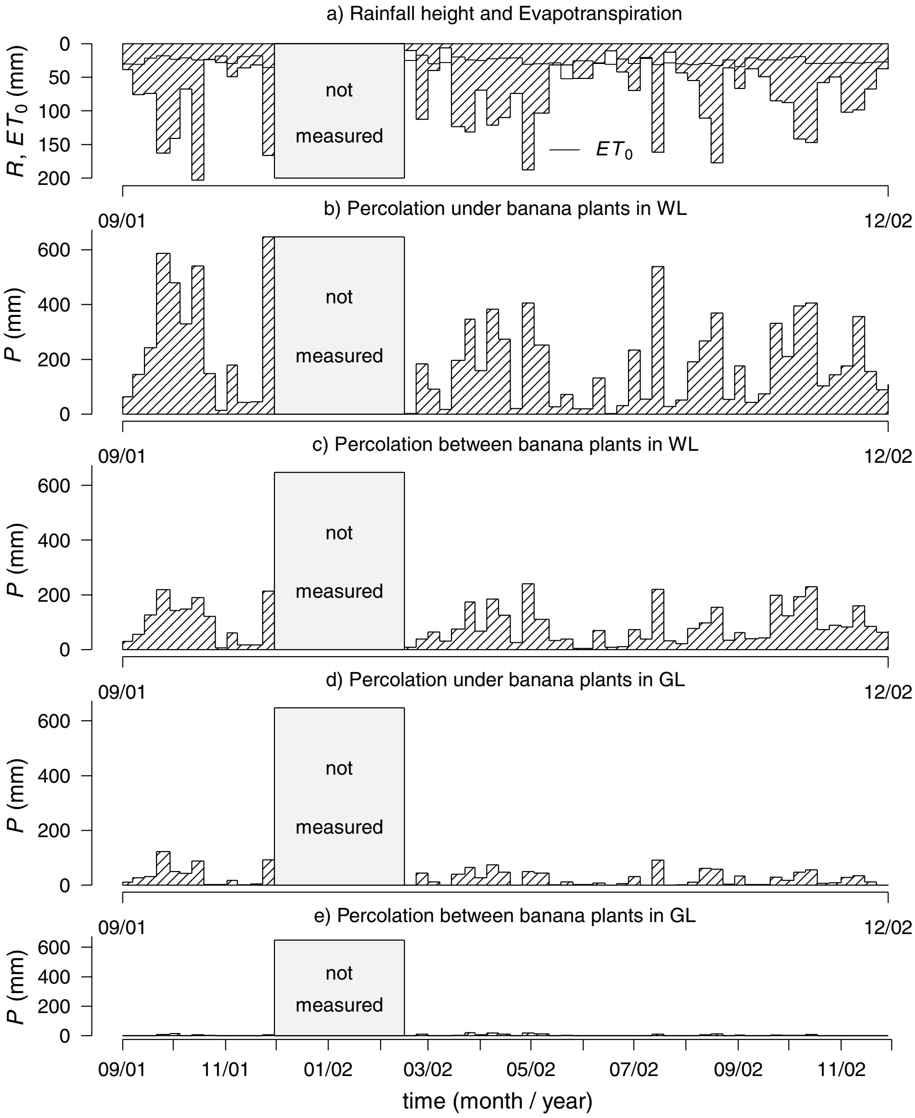

Figure 4 Weekly amounts of rainfall (*R*), evapotranspiration (ET_0) and percolation (*P*) fluxes under banana plants and between banana plants in the wick lysimeter (WL) and gravity lysimeter (GL).

increasingly higher than in GL as the initial water conditions reached saturation. One explanation is related to the fact that the WLs collect both saturated and unsaturated flow. As a consequence WL will begin percolating before GL and will stop after it.

Spatial variation in percolation fluxes

Spatial patterns

High spatial variation in percolation fluxes was noted over the monitoring period. The cumulated water volumes in

Table 1 Total rainfall (*R*), evapotranspiration (E_0), and percolation fluxes, calculated respectively on wick lysimeter and gravity lysimeter data, in areas under banana plants and between banana plants for the 390 days of the monitoring period

	R (mm)	E_0 (mm)	Estimated percolation fluxes[a] (mm)	Observed percolation fluxes (mm)	
				Wick lysimeter	Gravity lysimeter
Plot scale	4291	1444	2633	5803 (1332)[b]	351 (126)
Under banana	n.e.	n.e.	n.e.	10,890 (2180)	1499 (109)
Between banana	n.e.	n.e.	n.e.	5226 (1402)	221 (144)

n.e., not estimated.

[a] Estimated percolation fluxes = $R - r - E_0$ with r = Runoff = 5% $\times R$.

[b] Standard deviation of the mean in brackets.

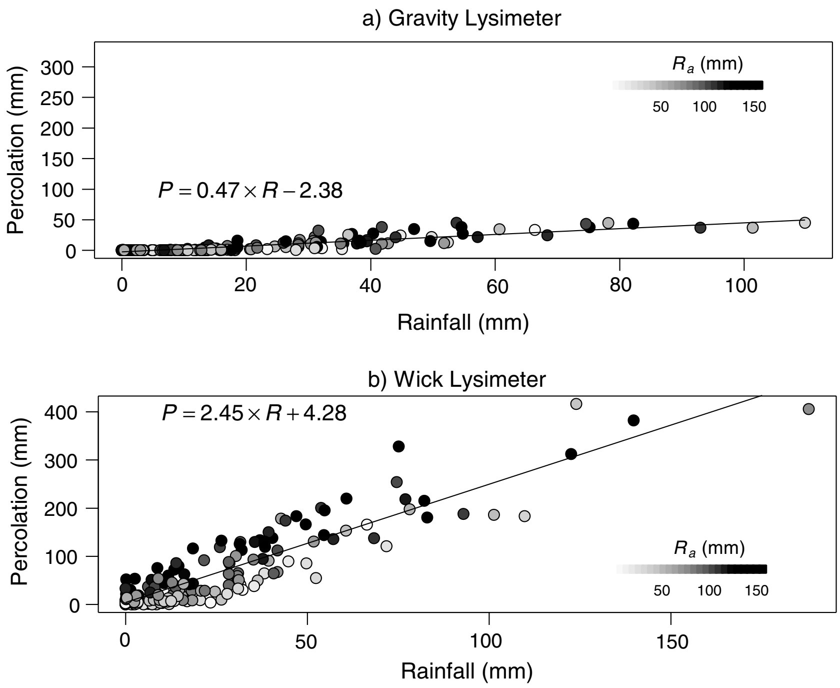

Figure 5 Relation between rainfall (R) and percolation (P) fluxes under banana plants: (a) in the gravity lysimeter; (b) in the wick lysimeter. Grey scale color represents the rainfall volume 48 h before the beginning of the elementary percolation period (R_a). Solid lines represent the curve of the regression between rainfall and percolation volumes.

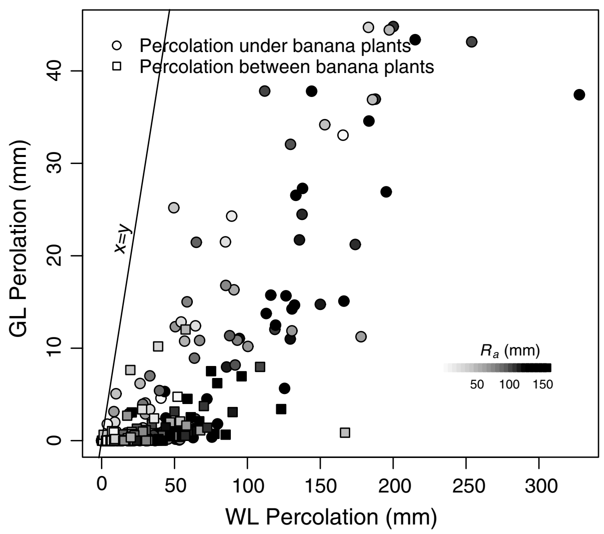

Figure 6 Relation between percolation under banana plants and between banana plants in the wick lysimeter (WL) and the gravity lysimeter (GL). Grey scale color represents the rainfall volume 48 h before the beginning of the elementary percolation period (R_a).

WL ranged from 2891 to 16,123 mm (mean 8058 mm; standard deviation (SD) 4548 mm; variation coefficient (CV) 56%), while in GL they ranged from 34 to 1812 mm (mean 860 mm; SD 723 mm; CV 84%). The source of this variability remained temporally steady, as indicated by the high linear correlation between the results obtained with the same type of sampler (Table 2 for WL), reflecting the steady volumetric percolation ratios between samplers. The highest percolation fluxes were always recorded via the same samplers.

Fig. 7 shows that spatial variations in percolation flux during the EPPs increased with the mean percolation volume, whereas the variation coefficient decreased. The variation coefficients were higher for GL as compared to WL (Fig. 7c and d). This difference of variation coefficients reflects the fact that for GL regardless the mean percolation flux there were always lysimeters exhibiting no flux, whereas for WL the minimum observed flux increased with the mean flux. It can be explained by the existence of a percolation threshold for GL. Finally, this high variability of percolation fluxes implies a low accuracy of the estimated mean percolation fluxes, especially for small percolated water fractions.

Influence of cropping patterns

Cumulated percolation fluxes measured under banana plants were higher than those measured between banana plants (Table 1). The results of a one-way analysis of variance with four replications showed significant differences between sites at the 1% level for GL and at the 10% level for WL. The site effect explained 89% of the total variance for GL and 44% for WL, thus confirming that this was a major determining factor, but not the only one. For WL, the ratio between the UB and BB percolation fluxes was 2.1. This was close although not equal to the ratio of rainfall volumes reaching the soil between the two sites, namely 2.8, as estimated in the Material and Methods, thus indicating that rainfall partitioning is a key factor with respect to the between-site percolation flux variability. We also noted that the UB to BB gravity percolation flux ratio was 6.8, i.e. much higher than the rainfall volume ratio; this is certainly to be

Table 2 Percolation correlation table during the elementary percolation period in the eight wick lysimeters (WL_1–WL_8)

	WL_1	WL_2	WL_3	WL_4	WL_5	WL_6	WL_7	WL_8
WL_1	1.00	0.80	0.81	0.78	0.75	0.73	0.84	0.78
WL_2		1.00	0.87	0.72	0.88	0.93	0.88	0.86
WL_3			1.00	0.79	0.82	0.79	0.89	0.85
WL_4				1.00	0.68	0.66	0.74	0.67
WL_5					1.00	0.94	0.90	0.89
WL_6						1.00	0.85	0.86
WL_7							1.00	0.91
WL_8								1.00

Lysimeters WL_1, WL_3, WL_5, WL_7 were between banana plants; lysimeters WL_2, WL_4, WL_6, WL_8 were under banana plants.

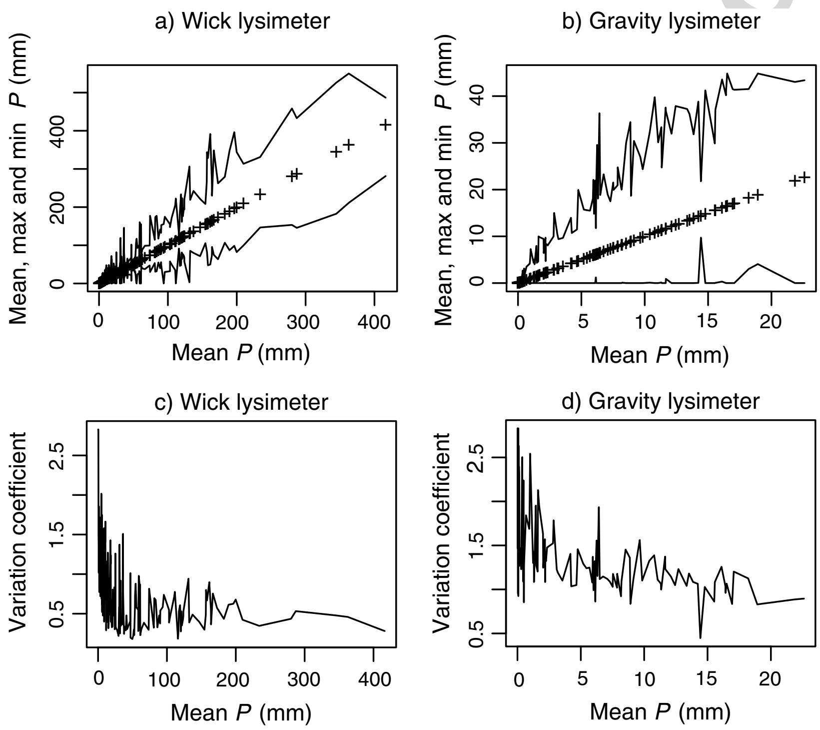

Figure 7 Variability in lysimeter measurements according to the mean percolation flux (*P*). Mean, maximum and minimum *P*: (a) in the wick lysimeter; (b) in the gravity lysimeter. Changes in the variation coefficient: (c) in the wick lysimeter; (d) in the gravity lysimeter.

related to the near absence of gravity percolation fluxes in BB. The differences in the performance of the two lysimetric systems indicates that rainfall partitioning under a canopy induced variations in the percolated water volumes, while also altering the nature of the percolation fluxes. Saturated percolation fluxes in BB were very small due to the reduction in incident rainfall.

The percolation flux differences discussed above were also confirmed at the EPP scale. For WL, the regression coefficient for UB percolation fluxes relative to those of BB was 2.1 (95% confidence interval: [2, 2.3]), which corresponds to the UB to BB cumulated percolation flux ratio over the monitoring presented in the previous paragraph. However, the rainfall class analysis (Fig. 8) showed that the percolation flux ratio between the two types of sites varied according to the rainfall patterns. It was much smaller than 2.0 for the two smallest classes of rainfall, and reached an almost constant value, averaging to 2.5, for rainfall classes above 20 mm.

Spatial variations in water potential

Curves plotted for the time-course tensiometric profiles (Fig. 9) highlighted two soil profile drying phases, in early and late March, linked with a reduction in rainfall. Drying was greater in the surface horizon under banana plants. It was also more marked than between banana plants where slighter drying occurred. This observation could be related to the distribution of roots, which are very dense near the surface at the base of banana plants (Gousseland, 1983). Root uptake thus partly counterbalanced the excessive water supply under banana plants. Apart from the drying periods, there was little difference between UB and BB at the soil surface when the potential values were high. How-

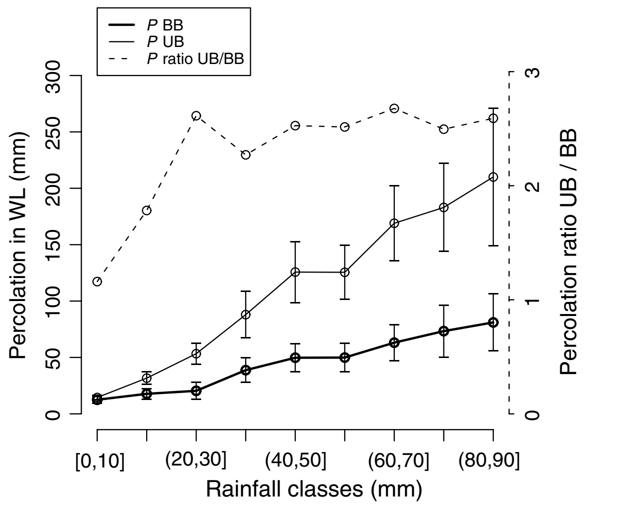

Figure 8 Percolation (P) under banana plants (UB) and between banana plants (BB) in the wick lysimeter, and percolation ratios at the two sites (UB and BB) according to rainfall classes. Only the first rainfall classes are showed because of the low number of elementary percolation periods.

ever, the potential at 50 cm depth was higher in UB, indicating that water accumulates at the plant base, with percolation flux occurring at deeper horizons, which is in line with results obtained elsewhere (Paltineanu and Starr, 2000; Starr and Timlin, 2004).

Discussion

Spatial variations in percolation fluxes

The extent of percolation flux measured under banana plants is consistent with the phenomenon of water concentration by plants previously described for other crops (Paltineanu and Starr, 2000; Timlin et al., 1992; Van Wesenbeeck and Kachanoski, 1988). The time consistency of this percolation under banana plants was not noted under the planting row of the crops studied in these reports. It could be correlated with the large and almost continuous rainfall conditions that prevail in our study region. This rainfall pattern hampers complete drying of the soil profile under banana plants, maintaining a soil water status close to that recorded between plants, as noted in the daily tensiometric data presented.

Considering the rainfall partitioning by banana plants, rainfall volumes on the soil surface at the UB and BB sites could be determined by applying the previously calculated rainfall partitioning coefficients, i.e. 2.36 and 0.85, respectively, for UB and BB, to the incident rainfall data. As shown in Fig. 10, the percolation data at sites UB and BB can be considered within the same percolation dynamic framework by relating the percolation values with the estimated rainfall amounts at the soil surface, instead of the incident rainfall. The regression calculated for the entire dataset accounted for 82% of the variance. This clearly confirms that the main source of percolation difference between UB and BB is the redistribution of rainfall by the banana canopy. When the initial water status, i.e. R_a, was introduced as a second predictor in the regression. The explained variance amounted to 88% (the differences in fit between the two models — with or without R_a — is very highly significant).

Nevertheless, the percolation ratios varied somewhat according to the rainfalls although their average value of 2.1 is close to 2.8, which is the rainfall ratio between UB and BB. It is likely that the percolation ratios computed for small rainfalls do also depend on differences in initial conditions. These are drier on average on sites UB than BB during periods with small rainfalls, as described in ''Spatial

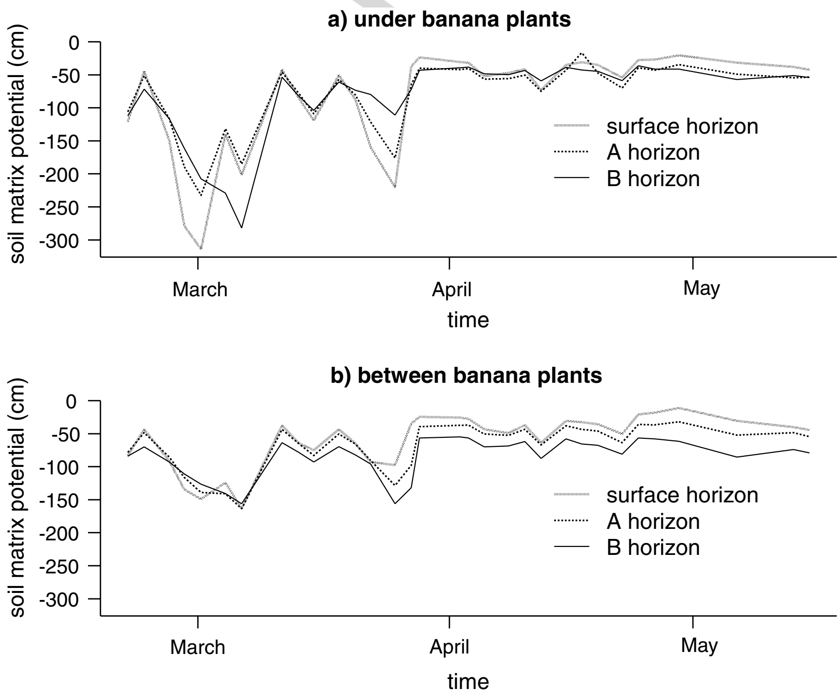

Figure 9 Variations in the soil matrix potential: (a) under banana plants; (b) between banana plants.

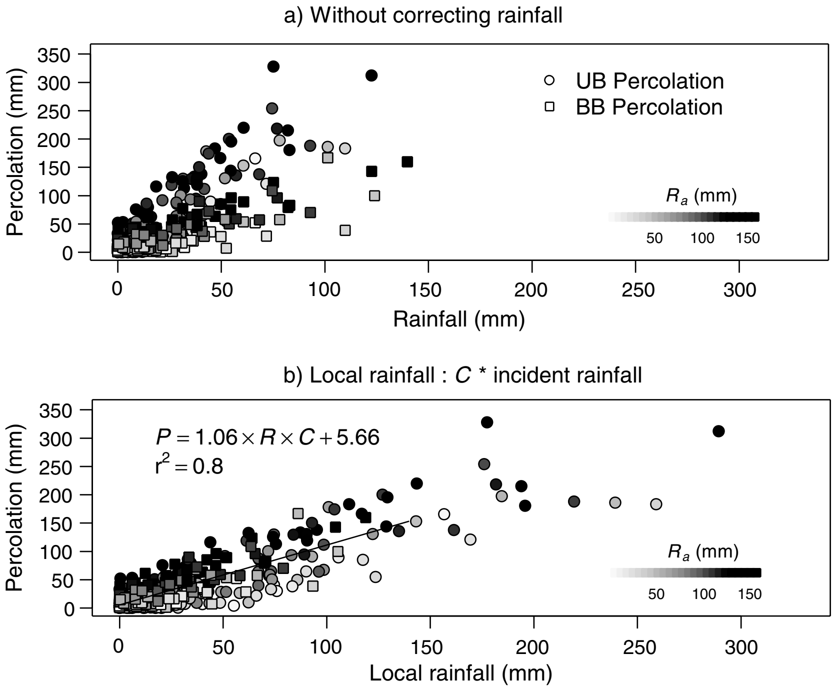

Figure 10 Effect of a distribution coefficient (C) on the relation between rainfall (R) and percolation (P) fluxes in the wick lyimeter under banana plants (UB) and between banana plants (BB): (a) no rainfall correction; (b) correction with C = 2.36 for UB and C = 0.85 for BB. The grey scale represents the amount of rainfall 48 h before the beginning of the elementary percolation period (R_a).

variations in water potential'', which can lead to minor somewhat the percolation fluxes on UB. Of course, the effect of the initial conditions will become insignificant with respect to the heterogeneous redistribution of rainfall by the canopy for larger rainfalls. This can then explain that the percolation ratio increases to 2.5 for the large rainfalls and comes closer to the estimated rainfall redistribution ratio of 2.8. There is however still a difference between the two ratios which may be explained by two factors. First, it may stem from the lateral diffusion of soil water after infiltration, and so, during rainfall, when stemflow water reaches the soil it would percolate via different pathways. These results are in line with the lateral row to interrow percolation fluxes observed by some authors (Arya et al., 1975; Timlin et al., 1992). Secondly, the 2.5 and 2.8 ratio difference could be explained by surface runoff transport (Paltineanu and Starr, 2000). Indeed, the 2.35-fold increase in rainfall water at the base of banana plants indicates that UB is a potential runoff departure zone, thus reducing the quantity of rainfall available for percolation under banana plants.

Number of samplers required

The advantage of taking into account the banana plantation pattern could be assessed from two calculations of the standard deviation of the average percolation flux at the plot scale. The first one, which does not take the spatial pattern into account, is the standard deviation of the cumulated water volumes reported ''Spatial patterns'' divided by the square root of the number of lysimeters. The Second one is the square root of the variance of the average percolation flux at the plot scale (V_{AP}), which was assessed according to Eq. (2) from the variances of the average percolation under banana plants (V_{UB}/n_{UB}) and between banana plants (V_{BB}/n_{BB}) weighted by the surface area of each site (S_{UB} and S_{BB} as defined in ''Climatic variables''), assuming the independence of the measurements between the two sites. Standard deviations of 1608 and 256 mm, for WL and GL, respectively, were obtained with the first calculation. They decreased to 1278 and 130 mm with the second calculation. To obtain these last values without considering the sites UB and BB, the number of lysimeters should have been raised from 8 to 13 for WL and for 8–31 for GL.

$$V_{AP} = (S_{UB}/S)^2 V_{UB}/n_{UB} + (S_{BB}/S)^2 V_{BB}/n_{BB} \qquad (2)$$

The number of samplers (n) required under banana plants (n_{UB}) and between banana plants (n_{BB}) to estimate the average percolation flux in field plots (AP) for a given mean accuracy level (d in %) could be calculated from Eq. (2) and from Eq. (3), stemmed from Holder et al. (1991).

$$d = 2\sqrt{V_{AP}}/AP \qquad (3)$$

Charts (Fig. 11) were drawn up to calculate n_{UB} and n_{BB} for different d values according to variances of the cumulated water volumes observed for each sites UB and BB. First, these charts highlight the difficulty to obtain accurate percolation flux measurements in the field due to the high CV values and owing the practical difficulty in increasing the number of samplers. Secondly, they show that the accuracy could be enhanced by taking the spatial patterns into account. Then, increasing n_{UB} beyond 5 has little incidence on d, particularly for GL despite the high percolation fluxes measured in this site, because the percolation in UB is weighted by the area S_{UB} and the accuracy is greater than in BB. On the other hand, an increase of n_{BB} is the main way to improve d. So new lysimeters should be installed preferentially in BB.

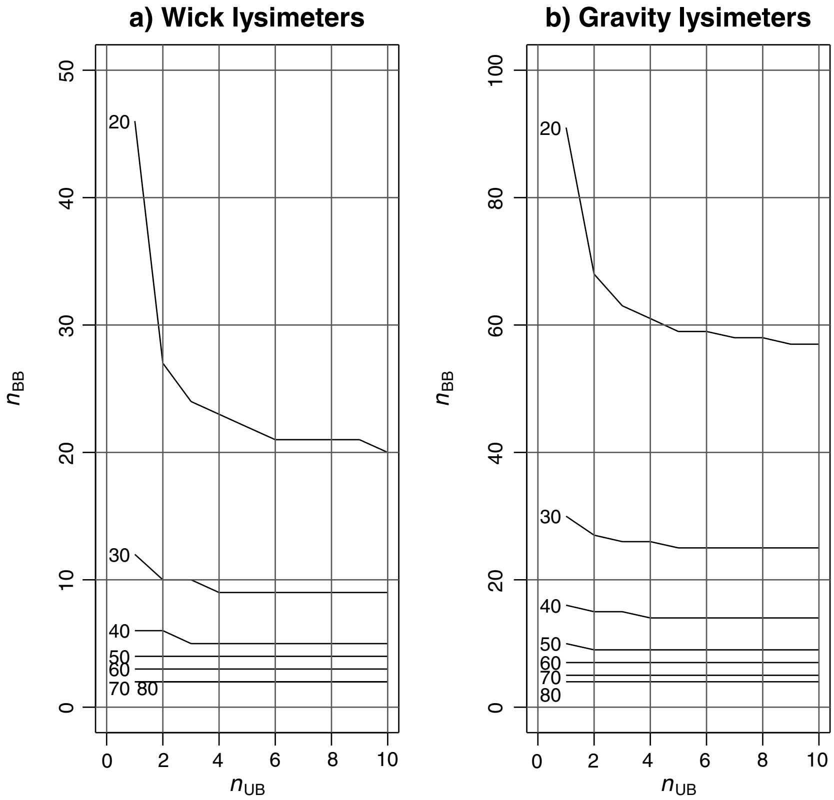

Figure 11 Curves of allowable error in the sample means in relation with the number of samplers under banana plants (n_{UB}) and between banana plants (n_{BB}) for: (a) the wick lysimeters; (b) the gravity lysimeters.

It was essential to take the spatial pattern of the variability induced by the crop into account to enhance the measurement accuracy, to integrate these measurements in the water balance calculations, and to assess differences in percolation/runoff partitioning induced by cropping practices.

Conclusion

This study highlights the unique features of wet tropical areas, where the rainfall conditions maintain a high soil water potential and are responsible for a virtually continuous percolation flux throughout the year, enhanced in the case of volcanic Andosols by their large infiltration properties. The work done aimed at examining the influence of cropping plants like banana on the spatial variation both in intensity and nature of the percolation fluxes on volcanic Andosols in Guadeloupe. The results obtained show several points.

First, the spatial variation of percolation fluxes appeared to be extremely large at the field scale and to be mainly generated by the rainfall partitioning that occurs in banana stands where the canopy redistributes preferentially rainfall by stemflow to the base of the banana plants. The ratio of percolation fluxes below and between banana plants was however slightly smaller than the rainfall ratio since lateral redistribution processes, either at the soil surface or in the soil matrix, are likely to have occurred. In addition a difference in the nature of the fluxes was also observed according to the distance to banana plants. Indeed, the studied Andosol exhibited generally much larger unsaturated flow than saturated flow since most rainfall intensities are not sufficient to saturate the very permeable Andosol. But given that rainfall redistribution by the canopy minored throughfall and favoured stemflow, saturated flow appeared negligible between the bananas whereas it was small but significant at the base of the banana plants.

Second, the observation of the large spatial variation of percolation fluxes indicates that to estimate the average percolation flux at the scale of a banana field with an acceptable precision requires a large number of sampling sites. It however also shows that the number of samples can be significantly reduced if a stratified sampling scheme according to the banana plantation patterns is chosen.

Third, the comparison of wick and gravity lysimeters confirmed earlier observations presented in the literature about these measurement devices: the wick lysimeters collect a higher percolation volume than the gravity lysimeters whereas gravity lysimeters tend to underestimate it. Moreover the former collect saturated and unsaturated flow, whereas the latter only collects saturated flow consisting probably of the most mobile soil water. Consequently, each of the two devices exhibit important bias in estimating soil percolation fluxes, but their simultaneous use enables to get estimates of boundary values of the actual flux and its nature, saturated and unsaturated.

Finally, this study can be seen as a very clear example of the influence of heterogeneous surface boundary conditions, that vegetation can cause, on the spatial variation of soil water fluxes. From an agronomic standpoint, the results of the study should help to improve pollution risk management in banana stands under tropical soil and climate conditions. In this constant percolation flux setting, there are actually no non-risk periods with respect to contamination of deep soil horizons and even the water table. The percolation flux distribution in field plots promotes leaching of fertiliser and pesticide compounds applied at the plant stem base, especially since percolation flux is higher in this zone. Fertiliser and pesticide treatment programmes should take the spatial heterogeneity in percolation fluxes into account, and especially avoid treatments in areas where percolation fluxes are intense. The temporal heterogeneity should also be considered by, for instance, taking the soil water status into account (rainfall within the previous 48 h), and by only applying fertilisers or pesticides after low rainfall periods in order to hamper early transport of these applied products.

Acknowledgements

We are grateful to Alexis Champoiseau, Aymeric Simon and Germain Onapin for their contribution to this work. This study was funded by the Guadeloupe Region (FWI), the Ministère de l'Ecologie et du Développement Durable (France) and the European Union under the project ''Assessment of water-pollution risks associated with agriculture in the French West Indies: management at the catchment scale''.

References

Abbaspour, K.C., Kohler, A., Simunek, J., Fritsch, M., Schulin, R., 2001. Application of a two-dimensional model to simulate flow and transport in a macroporous agricultural soil with tile drains. Eur. J. Soil Sci. 52 (3), 433–447.

Abdou, H.M., Flury, M., 2004. Simulation of water flow and solute transport in free-drainage lysimeters and field soils with heterogeneous structures. Eur. J. Soil Sci. 55 (2), 229–241.

Arya, L.M., Blake, G.R., Farrell, D.A., 1975. A field study of soil water depletion patterns in presence of growing soybean roots. II. Eects of plant growth on soil water pressure and water loss patterns. Soil Sci. Soc. Am. J. 39, 433–436.

Augeard, B., Kao, C., Chaumont, C., Vauclin, M., 2005. Mechanisms of surface runo genesis on a subsurface drained soil aected by surface crusting: a field investigation. Phys. Chem. Earth Parts A/B/C. Assessment of Anthropogenic Impacts on Water Quality 30 (8–10), 598–610.

Bassette, C., 2005. Modélisation 3-D de l'interception de la pluie par le bananier: eets des caractéristiques physiques du couverts sur les flux d'eau et d'énergie cinétique transmis au sol, Université Antilles-Guyane, Pointe-á-Pitre, pp. 153.

Bastergue, P., 1988. Mesure et estimation de l'évapotranspiration á la Guadeloupe. INRA CIRAD, Petit-Bourg, Guadeloupe, France.

Boll, J. et al, 1991. Water quality sampling under preferential flow conditions. In: Allen, R.G. (Ed.), Lysimeters for Evapotranspiration and Environmental Measurements. Proceedings of the ASCE International Symposium on Lysimetry, Honolulu, Hawai, 23–25 July 1991. Am. Soc. Civ. Eng., New York, pp. 290–298.

Boll, J., Steenhuis, T.S., Selker, J.S., 1992. Fiberglass wicks for sampling of water and solutes in the vadose zone. Soil Sci. Soc. Am. J. 56 (3), 701–707.

Bonan, H., Prime, J.L., 2001. Rapport sur la présence de pesticides dans les eaux de consommation humaine en Guadeloupe. rapport n°2001-070, Ministère de l'aménagement du territoire et de l'environnement – Ministère de l'emploi et de la solidarité, Paris, France.

Brandi-Dohrn, F.M., Dick, R.P., Hess, M., Selker, J.S., 1996. Field evaluation of passive capillary samplers. Soil Sci. Soc. Am. J. 60, 1705–1713.

Brye, K., Norman, J., Bundy, L., Gower, S., 1999. An equilibrium tension lysimeter for measuring drainage through soil. Soil Sci. Soc. Am. J. 63 (3), 536–543.

Castillo, L.E., Ruepert, C., Solis, E., 2000. Pesticide residues in the aquatic environment of banana plantation areas in the north Atlantic zone of Costa Rica. Environ. Toxicol. Chem. 19 (8), 1942–1950.

Cattan, P., Bussière, F., Nouvellon, A., in press. Evidence of large rainfall partitioning patterns by banana and impact on surface runo generation. Hydrol. Process.

Cattan, P., Cabidoche, Y.-M., Lacas, J.-G., Voltz, M., 2006. Eects of tillage and mulching on runo under banana (Musa spp.) on a tropical Andosol. Soil Till. Res. 86 (1), 38–51.

Clothier, B.E., Vogeler, I., Magesan, G.N., 2000. The breakdown of water repellency and solute transport through a hydrophobic soil. J. Hydrol., 255–264.

Colmet-Daage, F., Lagache, P., 1965. Caractéristiques de quelques groupes de sols dérivés de roches volcaniques aux Antilles françaises. Cahiers de l'ORSTOM serie pédologie 8, 91–121.

Dunne, T., Zhang, W., Aubry, B.F., 1991. Eects of rainfall, vegetation, and microtopography on infiltration and runo. Water Resour. Res. 27 (9), 2271–2285.

FAO, 1990. Soil Units of the Soil Map of the World. FAO-UNESCO-ISRIC, Roma, Italy.

Gascuel-Odoux, C., Bruneau, P., Curmi, P., 1991. Runo generation: assessment of relevant factors by means of soil microtopography and micromorphology analysis. Soil Technol. 4 (3), 209–219.

Gousseland, J., 1983. Etude de l'enracinement et de l'émission racinaire du bananier 'Giant Cavendish (Musa acuminata AAA, sous-groupe Cavendish) dans les andosols de la Guadeloupe. Fruits 38 (9), 611–623.

Goyne, K.W., Day, R.L., Chorover, J., 2000. Artifacts caused by collection of soil solution with passive capillary samplers. Soil Sci. Soc. Am. J. 64, 1330–1336.

Hangen, E., Gerke, H.H., Schaaf, W., Huttl, R.F., 2005. Assessment of preferential flow processes in a forest-reclaimed lignitic mine soil by multicell sampling of drainage water and three tracers. J. Hydrol. 303 (1–4), 16–37.

Holder, M., Brown, K.W., Thomas, J.C., Zabcik, D., Murray, H.E., 1991. Capillary-wick unsaturated zone soil pore water sampler. Soil Sci. Soc. Am. J. 55 (5), 1195–1202.

Jimenez, O.F., Lhomme, J.P., 1994. Rainfall interception and radiation regime in a plantain canopy. Fruits 49 (2), 133–139.

Kirkby, M., 2002. Modelling the interactions between soil surface properties and water erosion. CATENA 46 (2–3), 89–102.

Knutson, J.H., Selker, J.S., 1994. Unsaturated hydraulic conductivities of fiberglass wicks and designing capillary wick porewater samplers. Soil Sci. Soc. Am. J. 58 (3), 721–729.

Kosugi, K., Katsuyama, M., 2004. Controlled-suction period lysimeter for measuring vertical water flux and convective chemical fluxes. Soil Sci. Soc. Am. J. 68 (2), 371–382.

Lacas, J.-G., Voltz, M., Cattan, P., 2004. Numerical evaluation of passive capillary samplers. EGU General Assembly 2004. Geophysical Research Abstracts, Nice, France.

Landon, M.K., Delin, G.N., Komor, S.C., Regan, C.P., 1999. Comparison of the stable-isotopic composition of soil water collected from suction lysimeters, wick samplers, and cores in a sandy unsaturated zone. J. Hydrol. 224 (1/2), 45–54.

Levia Jr., D.F., Frost, E.E., 2003. A review and evaluation of stemflow literature in the hydrologic and biogeochemical cycles of forested and agricultural ecosystems. J. Hydrol. 274 (1–4), 1–29.

Magesan, G.N., White, R.E., Scotter, D.R., 1995. The influence of flow rate on the concentration of indigenous and applied solutes in mole-pipe drain euent. J. Hydrol. 172 (1—4), 23—30.
Météo-France, 1999. Bulletin Climatologique Annuel 1999, Service Régional de Guadeloupe, Les Abymes.
Paltineanu, I.C., Starr, J.L., 2000. Preferential water flow through corn canopy and soil water dynamics acress rows. Soil Sci. Soc. Am. J. 64, 44—54.
Poulenard, J., Michel, J.C., Bartoli, F., Portal, J.M., Podwojewski, P., 2004. Water repellency of volcanic ash soils from Ecuadorian paramo: eect of water content and characteristics of hydrophobic organic matter. Eur. J. Soil Sci. 55 (3), 487—496.
Reynolds, W.D., Elrick, D.E., 1991. Determination of hydraulic conductivity using a tension infiltrometer. Soil Sci. Soc. Am. J. 55 (3), 633—639.
Starr, J.L., Timlin, D.J., 2004. Using high-resolution soil moisture data to assess soil water dynamics in the vadose zone. Vadose Zone J. 3, 926—935.
Timlin, D.J., Heathman, G.C., Ahuja, L.R., 1992. Solute leaching in crop row vs interrow zones. Soil Sci. Soc. Am. J. 56, 384—392.
van der Velde, M., Green, S.R., Gee, G.W., Vanclooster, M., Clothier, B.E., 2005. Evaluation of drainage from passive suction and nonsuction flux meters in a volcanic clay soil under tropical conditions. Vadose Zone J. 4 (4), 1201—1209. doi:10.2136/vzj2005.0011.
Van Wesenbeeck, I.J., Kachanoski, R.G., 1988. Spatial and temporal distribution of soil-water in the tilled layer under a corn crop. Soil Sci. Soc. Am. J. 52, 363—368.
Wenner, D.B., Ketcham, P.D., Dowd, J.F., 1991. Stable isotopic composition of waters in a small Piedmont watershed. In: Taylor, J.H.P., O'Neil, J.R., Kaplan, I.R. (Eds.), Stable Isotope Geochemistry: A Tribute to Samuel Epstein. The Geochemical Society, pp. 195—203.
Zhu, Y., Fox, R.H., Toth, J.D., 2002. Leachate collection eciency of zero-tension pan and passive capillary fiberglass wick lysimeters. Soil Sci. Soc. Am. J. 66, 37—43.

4 Hydrological behaviour and modelling of a volcanic tropical cultivated catchment.

HYDROLOGICAL PROCESSES
Hydrol. Process. **22**, 4355–4370 (2008)
Published online 27 May 2008 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/hyp.7040

Hydrological behaviour and modelling of a volcanic tropical cultivated catchment

Jean-Baptiste Charlier,[1]* Philippe Cattan,[1] Roger Moussa[2] and Marc Voltz[2]

[1] *CIRAD, UPR Systèmes bananes et ananas, Capesterre-Belle-Eau, Guadeloupe, F-97130, France*
[2] *INRA, Laboratoire d'étude des Interactions Sol-Agrosystème-Hydrosystème (LISAH), UMR AgroM-INRA-IRD, Bat. 24, 2 place Viala, 34060 Montpellier cedex 1, France*

Abstract:

The hydrological behaviour of the cultivated Féfé catchment (17·8 ha) on the tropical volcanic island of Guadeloupe was studied to identify flow paths, to quantify water fluxes, and finally, to build a lumped model to simulate discharge and piezometer levels. The approach combined two steps, an experimental step and a modelling step, which covered two time scales, the annual and the storm event scale. The hydrological measurements were conducted over 2 years. The Féfé catchment is characterized by heavy rainfall (4229 mm year^{-1}) on permeable Andosols; the results showed that underground flow paths involved two overlapping aquifers, and that the annual water balance in 2003 was shared among outflows of the deep aquifer (42%), evapotranspiration (31%), and streamflow (27%). On the event scale, the surface runoff coefficient ranges between 6·2% and 24·4% depending on antecedent dry or wet moisture conditions. Hortonian overland flow predominated over subsurface and saturation overland flow processes. Recharge of the shallow aquifer is mainly governed by a constant infiltration capacity of the Andosols with depth in the vadose zone. Outflows of this shallow aquifer were the baseflow of the main stream and the recharge of the deep aquifer. Volcanic deposits at Féfé promoted the underground flow path, and cultivated areas seemed to explain the high stormflow values relative to other tropical small catchments under rain forest. A conceptual lumped model integrating runoff, infiltration, evapotranspiration, and fluctuations of the two overlapping aquifers was developed. The model has six parameters and was calibrated and validated on the hydrograph at the outlet and on the two piezometers of the shallow and the deep aquifers. The results show fair to good agreement between measured and simulated variables, and consequently, the model was consistent with the main hydrological processes observed from experimental results in wet conditions.

KEY WORDS hydrological processes; cultivated catchment; tropical; lumped model; water balance; volcanic aquifer

Received 21 March 2007; Accepted 28 February 2008

INTRODUCTION

The study of hydrological processes in humid tropical areas has been well documented (Bonell, 1993; Elsenbeer, 2001), but there is a lack of knowledge with regard to volcanic regions, where the framework generates high spatial and vertical variability of flow paths. In the humid tropical climate, characterization of the main hydrological processes may be complicated by large seasonal variations in all aspects of the water balance (Cook *et al.*, 1998). In volcanic regions, deposits are characterized by polygenetic materials with high contrasts in permeability (Lachassagne, 2006). However, the study of hydrological cultivated systems is a key issue in the West Indies and Central America, where agriculture is widespread in coastal volcanic areas and where pressure from human activities is high (Rawlins *et al.*, 1998). Thus, it requires the identification of surface and underground flow paths and the quantification of water fluxes. In this setting, the present article focuses on hydrological processes and modelling approaches in a small, cultivated catchment on a humid tropical volcanic island.

Previous studies in tropical small catchments (less than 100 ha) under forest cover on highly permeable soils reported a water balance essentially shared between evapotranspiration and runoff, and without a significant underground outflow component (Bruijnzeel, 1983; Lesack, 1993; Fujieda *et al.*, 1997; Kinner and Stallard, 2004). As in many other tropical sites on permeable soils, and reported in three reviews by Dubreuil (1985), Bonell (1993) and Elsenbeer (2001), a sharp decrease in the infiltration capacity with soil depth promoted subsurface stormflow (SSSF) on hillslopes, and wet land areas close to the channel promoted saturation overland flow (SOF); Hortonian overland flow (HOF) is often limited to local areas on hillslopes. Different factors may explain the variability of overland flow. The first key factor is the land use pattern: deforestation and agriculture significantly increase the surface runoff coefficient on a storm-event scale (Fritsch, 1992; Bruijnzeel, 2004). A second key factor is the soil infiltration rate, which is typically high in volcanic ash soils (for a review see Dahlgren *et al.*, 2004). Therefore, the runoff coefficient is just a few percent at the plot scale (Buytaert *et al.*, 2006; Cattan *et al.*, 2006) and the catchment scale (Bruijnzeel, 1983).

* Correspondence to: Jean-Baptiste Charlier, CIRAD, UPR Systèmes bananes et ananas, Capesterre-Belle-Eau, Guadeloupe, F-97130, France. E-mail: jb.charlier@gmail.com

On the other hand, the challenge in assessing underground transfers is complicated by the geometry of volcanic deposits. This is the situation in Guadeloupe, where a soil survey highlighted the marked vertical and horizontal lithological discontinuity of recent deposits and the permeability of the bedrock, which does not slow down water infiltration to deep horizons (Colmet-Daage, 1969). This promotes the development of overlapping aquifer systems (Join *et al.*, 1997; Lachassagne, 2006), along with percolation, which recharges deep aquifers.

It is currently difficult to extend the results of hydrological behaviour of small humid tropical catchments to other cultivated sites on volcanic deposits for three main reasons: (i) most of the observations in humid tropical catchments are under forest cover where geomorphological and pedological properties promote SSSF and SOF, instead of cultivated areas where HOF can become a main mechanism of stormflow (Fritsch, 1992; Malmer, 1996; Zimmermann *et al.*, 2006); (ii) underground flows in tropical environments have not been well documented, as mentioned by Lesack (1993) and Cook *et al.* (1998); (iii) to our knowledge, only one previous study has been carried out on volcanic deposits at the intermediate scale of the catchment (Bruijnzeel, 1983). Other studies in volcanic areas were mainly conducted at the plot scale (Poulenard *et al.*, 2001; Fontes *et al.*, 2004; Van Dijk and Bruijnzeel, 2004; Cattan *et al.*, 2006) or at the regional scale (Ecker, 1976; Join *et al.*, 1997; Scholl *et al.*, 1998). In this setting, TOPMODEL approaches have been used for tropical catchments in the Ivory Coast (Quinn *et al.*, 1991), in French Guyana (Molicova *et al.*, 1997) and Central Panama (Kinner and Stallard, 2004) to verify the hypothesis of a predominance of SSSF and SOF. But although the main reasons why this model was successful relate to an impeding subsoil layer coupled with the absence of an additional deep groundwater body, it cannot take into account the hypothesis of specific properties of some porous volcanic frameworks in cultivated areas such as HOF under high rainfall intensities and percolation to deep groundwater compartments. Thus, it is important to focus on hydrological processes in tropical volcanic areas.

The present study aims to establish the hydrological behaviour of a small, cultivated tropical catchment and to develop a simple model to simultaneously simulate the hydrograph and the aquifer levels. The approach combined two steps, an experimental and a modelling step, and covered two time scales, the annual and the storm event scales. The paper is structured in four parts: (i) presentation of the study site, the Féfé catchment in Guadeloupe; (ii) a methodology to analyse hydrometeorological data; (iii) quantification of the terms of the water balance at the annual scale and determination of relationships between water compartments at the event scale in which a behavioural scheme is presented; and (iv) on the basis of this scheme, development of a conceptual lumped model to simulate both stormflow and groundwater fluctuations; the last step consists of a multi-criteria model calibration and validation.

STUDY SITE

Site description

Presentation. The Féfé catchment (16°03′50″N, 61°37′12″W) is located on the south-east side of the volcanic island of Basse Terre, Guadeloupe (French West Indies) (Figure 1). It covers an area of 17·8 ha, extending in a NW–SE direction along the slopes of La Soufrière, the Guadeloupe volcano. It is rectangular, with mean dimensions 260×680 m and an elevation range of 318–428 m ASL. It is divided, lengthwise, into two geomorphologically different zones. The northern half is a hillslope with steep 26–60% slopes. The southern half consists of a short plateau with a mean 9% slope, which is continuously drained by the main stream. The catchment cuts across five farms, with 55% of the catchment area covered by banana (*Musa* spp.), 40% of the fallow land covered by flowers and grass and 5% used for human infrastructures, including roads, platforms and sheds.

Climate. The West Indies are under a maritime humid tropical climate with two distinct seasons, a dry season in February–March and a rainy season from July to November (Morell and Jérémie, 1994). February is statistically the driest month of the year at the Neufchâteau research station (16°04′38″N, 61°36′04″W, 250 m ASL), which is the closest station to the catchment. Therefore, for this case study, the hydrological year was set to begin on 1 February and end on 31 January of the next year. The rainfall intensity is high on the eastern slopes of Basse Terre: the rainfall depth return period of 2 years for 30 and 60 min are 30 and 42 mm, respectively (Chaperon *et al.*, 1983). At the Neufchâteau station, the interannual average for rainfall between 1952 and 2004 was 3636 mm, and annual rainfall for 2003 and 2004 were 3676 and 6558 mm, respectively (Météo-France, 2005). The monthly distribution of rainfall (Figure 2) shows that the year 2003 was close to the average year and that the year 2004 was exceptionally rainy in May and November.

Geology and soil survey. On the island of Basse Terre, volcanic deposits are of andesitic–dacitic to andesitic composition (Dagain *et al.*, 1981; Boudon *et al.*, 1987). A geological survey of the Féfé sector, especially on the basis of core samples extracted at two drilling sites in the catchment (FF and FH—Figure 1), highlighted three different compartments, which were (from the deepest to the most superficial): (i) weathered breccias defined as the impermeable substratum; (ii) nuees ardentes (pyroclastic deposits including ash, pumice and rock debris) associated with andesitic lava flows poured out within depressions incised in the substratum, i.e. palaeovalleys oriented WNW-ESE; and (iii) weathered pumiceous lapillis (Figure 3). The profile of the superficial formation consisted of four superposed 0·5–2·0 m pyroclastic deposits rich in lapillis that were partially altered on the top half of each layer. At the base of this formation, a weathered ash layer over 1 m thick with low porosity, located at 4·5–6 m depth according to the core samples FF and

DOI: 10.1002/hyp

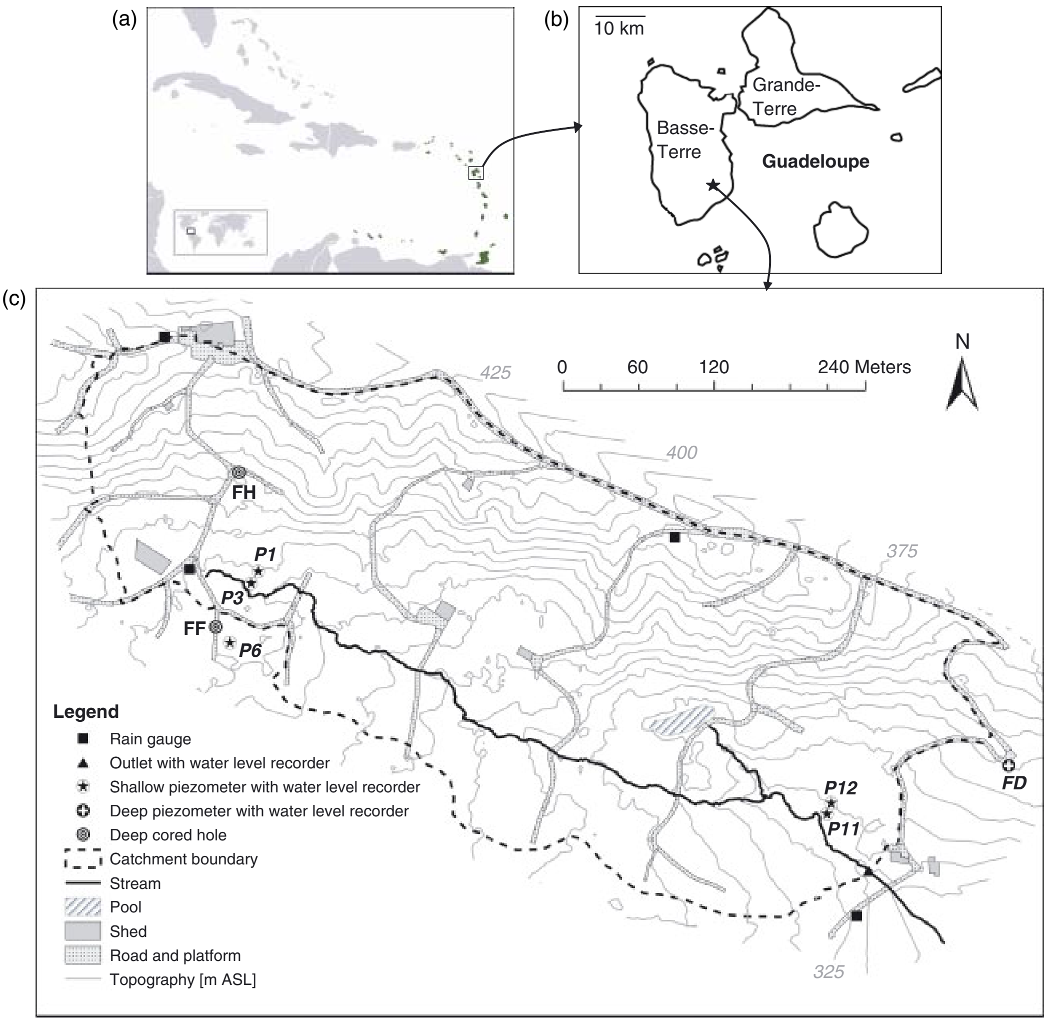

Figure 1. Maps of the Caribbean islands, location of the Lesser Antilles (black) (a) and the Guadeloupe archipelago (French West Indies) (b) indicating the location of the Féfé catchment. Contour map of the Féfé catchment (c) showing the location of equipment

FH, seems to explain the presence of a saturated zone in this superficial formation. From a pedological standpoint, alteration of the superficial formations had given rise to an umbric Andosol (WRB, 2006), which was extensively studied by Dorel *et al.* (2000) in the Féfé area.

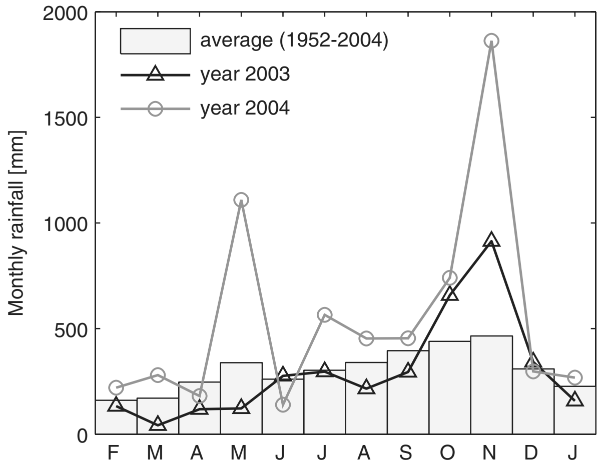

Figure 2. Monthly distribution of rainfall at Neufchâteau station from February until January (from Météo-France, 2005)

Field methods

The locations of the monitoring sites are shown in Figure 1. Rainfall intensities were measured at four sites using tipping bucket rain gauges (ARG100, Campbell Scientific, Shepshed, Leicestershire, UK), with a sensitivity of 0·2 mm of rain per tip. Potential evapotranspiration (PET) was calculated from daily global radiation (Rg) measured at the Neufchâteau station using a pyranometer (SP1110, Campbell Scientific) according to a formula determined experimentally in the Guadeloupe archipelago (Morell and Jérémie, 1994):

$$PET = 0{\cdot}24Rg \tag{1}$$

with PET in mm day^{-1} and Rg in MJ m^{-2} day^{-1}. Given the nonlimiting water supply conditions at the humid tropical Féfé catchment, we assumed that the actual evapotranspiration (ET) was considered as being equal to PET.

The gauging station at the catchment outlet consisted of a composite weir with (i) a 90° V-notch, 0–0·50 m high, (ii) overlaid by a 1·95 m wide, 0·50–1·025 m high, rectangular weir, and (iii) for exceptional flood events, the shape of the outlet section above 1·025 m is assumed

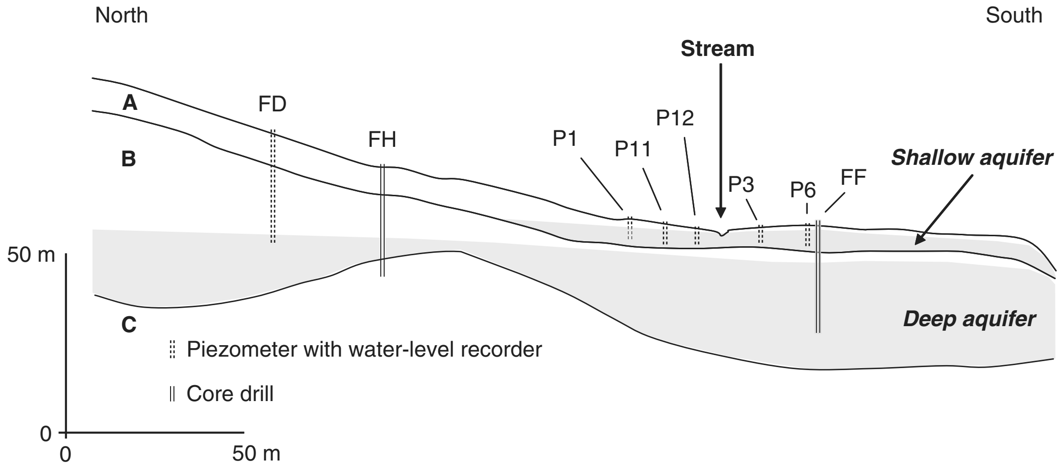

Figure 3. Hydrogeological diagram of the Féfé catchment: (A) weathered pumiceous lapillis; (B) nuees ardentes (pyroclastic deposits including ash, pumice and rock debris) associated with andesitic lava flows; (C) weathered breccias (impermeable substratum)—in grey, illustration of the saturated zones of the two overlapping aquifers

to be trapezoidal. Water levels were recorded on a 2 min time step using a PDCR1830 depth and level sensor (Campbell Scientific).

Two types of piezometers were set up to assess the hydrogeological features of the catchment (Figures 1 and 2): five shallow piezometers (P1, P3, P6, P11 and P12) perforated in the superficial formation, and three deep piezometers (FD, FF and FH) perforated in the underlying nuees ardentes associated with lava flow formation and isolated from the superficial formation by a clay plug in the upper part of the borehole. First, in all piezometers, manual water levels measured revealed the presence of two overlapping aquifers, i.e. a shallow aquifer in the weathered pumiceous lapillis layer and a deep aquifer in the layer consisting of nuees ardentes associated with lava flows. In contrast with the deep aquifer, the shallow aquifer is drained by the main stream of the Féfé catchment. Second, the five shallow P1, P3, P6, P11 and P12 piezometers and the deep FD piezometer were equipped with pressure sensors (Diver, Van Essen Instruments, Delft, NL) to measure water levels on a 4 min time step. Piezometric levels recorded automatically were calibrated against manual weekly measurements. The piezometric time series were recorded over the 16/12/2003 to 31/01/2005 period.

A double ring infiltrometer (Bouwer, 1986) helped to determine infiltration rates. Before measurements, the soil was saturated over 24 h. During the test, a constant water head of 10 mm was maintained in both rings, with a 30 cm inner diameter and 60 cm outer diameter cylinder inserted 3 cm into the soil. Water entering the soil was measured with a calibrated Mariotte bottle at a 10 min time step for 2 h (three replicates). The infiltration rate is calculated from the rate of fall of water in the reservoir. Twenty-eight saturated hydraulic conductivity (Ks) measurements were taken in the surface organic horizon and six were recorded in the weathered horizon at 40 cm depth.

DATA PROCESSING

Hydrological data

To relate rainfall to streamflow and underground fluctuations, and to quantify water fluxes at the annual scale in the catchment, the five time series of rainfall, evapotranspiration, discharge, shallow, and deep water level were synchronized on a 2 min time step over the 01/02/2003 to 31/01/2005 period. For rainfall, measurements from each rain gauge were integrated over a 2 min time step, and the average catchment rainfall was estimated by the arithmetic mean of the rainfall values observed at the four gauges. Owing to a technical problem at Féfé, rainfall data for the 30/04/2004 08:26 to 14/05/2004 09:46 period were replaced by the rainfall data from the Neufchâteau station (recorded on the same equipment as that used at the Féfé catchment) with a correction factor. This correction factor was determined at a daily time step from the comparison of rainfall time series recorded in 2003 at the Féfé catchment and at the Neufchâteau station. For adjustment (determination coefficient of the linear fit: $r^2 = 0{\cdot}48$), only daily values in the same range of measured rainfall depth at the Neufchâteau station during this period (i.e. 0 to 25 mm day^{-1}) were selected. Evapotranspiration was considered constant throughout the day (24 h). Since the piezometric measurements were recorded on a 4 min time step, the observed data were interpolated to obtain a time series on a 2 min time step. The determination coefficients between the five shallow piezometers (P1, P3, P6, P11 and P12) ranged from 0·59 to 0·94 (Table I). This result indicates that the variations in the shallow water levels in these piezometers were similar, and fair correlations existed between downstream (P11 and P12) and upstream (P1, P3 and P6) piezometers. A mean shallow water depth time series z_{SA}, was established, which corresponded to the arithmetic mean of the depths for all five piezometers. The z_{SA} correlation coefficients calculated relative to data collected from the other piezometers ranged from 0·77 to 0·94, thus confirming that this piezometer mean was representative. Concerning the FD piezometer, the water table depth is noted as z_{DA}. Hereafter, therefore, the focus is on the z_{SA} and z_{DA}, which characterized the water table depth of the shallow and the deep aquifers, respectively.

Terms of the water balance

For assessment of the water balance of the global hydrological system, two equations were used representing the water balance of the two overlapping aquifers

for the shallow aquifer (mm):

$$D + \Delta W_{SA} = P - ET - R \quad (2)$$

for the deep aquifer (mm):

$$O_{DA} + \Delta W_{DA} = D \quad (3)$$

where D is the losses of the shallow aquifer and the recharge of the deep aquifer, ΔW_{SA} the variation in the shallow aquifer stock, P rainfall, ET evapotranspiration, R streamflow, O_{DA} outflows of the deep aquifer, and ΔW_{DA} the variation in the deep aquifer stock. P and R were measured, ET was calculated from Equation (1), and D, ΔW_{SA}, O_{DA}, and ΔW_{DA} were residual terms of the equations. At the beginning of each hydrological year corresponding to a dry period, groundwater levels were similar enough to consider that water stock variations were negligible ($\Delta W_{SA} = \Delta W_{DA} = 0$) in the case of abundant annual rainfall. Consequently, on an annual scale, outflows of the global system were O_{DA}.

Time series partitioning

To evaluate the response of the catchment, two types of time series partitioning were performed. First, to relate a rainfall event to the corresponding runoff generation and to the corresponding shallow and deep aquifer recharges, partitioning was aimed at delimiting storm events according to criteria on rainfall intensity, flow, and water table depth. Second, to characterize the effect of initial conditions, partitioning was aimed at classifying these storm events according to their antecedent moisture condition.

The first partitioning was based on the delimitation of storm events (Figure 4). The following criteria were used for partitioning: (i) the rainfall event begins when the rainfall intensity is greater than 0·5 mm h^{-1} for 2 h, and ends when rainfall intensity drops under this threshold for 2 h; (ii) the flow increases by more than 0·003 m^3 s^{-1}. Overall, 310 storm events involving rainfall associated with a flood were partitioned (variations of event characteristics: 0·8–61·7 h for duration, 1·5–577 mm for rainfall, 0·004–4·6 m^3 s^{-1} for maximum discharge). The two components of the streamflow volume at the outlet R (Equation (4)) were the stormflow (S), representing runoff associated with overland flow and return of subsurface water with short residence time in the catchment, and the baseflow (B), representing returned groundwater from the shallow aquifer.

$$R = B + S \quad (4)$$

where R is the streamflow depth, S is the stormflow depth, and B is the baseflow depth. The stormflow coefficient is defined as S/P in per cent. S and B were separated according to the straight line method between the beginning point of the stormflow and the beginning of the recession curve (Chow *et al.*, 1988). This method considers that the recession curve takes the form of an exponential decay that is linearized on a logarithmic scale. Thus, the beginning of the recession curve is graphically determined at the beginning of the linear part of the curve plotted on a semi-logarithmic scale (Figure 4). The baseflow increased linearly during the basewidth (between $Q_{S\ i}$ and $Q_{S\ f}$ in Figure 4). In some cases, the location of $Q_{S\ f}$ is not accurate; consequently, the calculation of B is relatively sensitive to $Q_{S\ f}$ instead of S, which is less dependent. Thus, in this paper, only S/P will be discussed. Of all of these storm events, 66 flash storm events of short duration occurred, with a relatively high mono-peak discharge (example of a flash storm event shown in Figure 4). S/P, and the catchment response time, the time between the rainfall centre of gravity t_{Pg} and the peak flow t_{Qmax} (Roche, 1963), were calculated. The shallow water table variations (z_{SA}) ranged from 0·5 to 2·5 m and were fast enough to observe a rise in the mean piezometric water level during a storm event (Figures 3 and 4). Here, dz_{SA} is defined as the positive shallow water table fluctuation between initial depth $z_{SA\ i}$ and the minimal water table depth $z_{SA\ min}$ ($dz_{SA} = z_{SA\ i} - z_{SA\ min}$). dz_{SA} was calculated for 36 flash storm events with total rainfall greater than 10 mm in order to limit error concerning small rainfall.

The second partitioning was based on an antecedent moisture condition indicator, baseflow, and led to the identification of three periods: DRY, TRANS (i.e. transitional) and WET. Baseflow at Féfé ranged between 0 and 0·094 m^3 s^{-1} and the following baseflow classes were defined: (i) under 5×10^{-3} m^3 s^{-1} (DRY), mainly observed during the dry season; (ii) 5–20 $\times 10^{-3}$ m^3 s^{-1} (TRANS), mainly observed during rainy season; and (iii) over 20×10^{-3} m^3 s^{-1} (WET), observed only when major tropical storms occur (Figure 5). Intuitively, this baseflow represents the water storage depth in the superficial formation.

Table I. Determination coefficient (r^2) matrix for water depths with five shallow piezometers and mean shallow water depth (z_{SA})

	P1	P3	P6	P11	P12	z_{SA}
P1	1·00					
P3	0·88	1·00				
P6	0·86	0·92	1·00			
P11	0·59	0·64	0·66	1·00		
P12	0·72	0·67	0·62	0·69	1·00	
z_{SA}	0·94	0·94	0·94	0·77	0·79	1·00

DOI: 10.1002/hyp

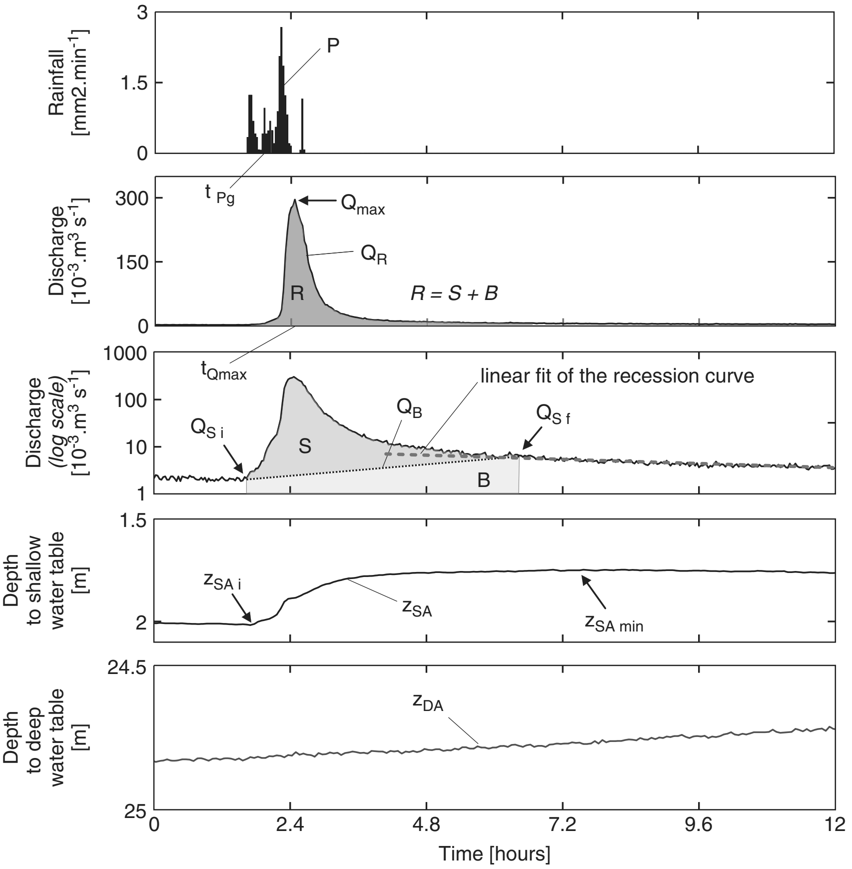

Figure 4. Characteristics of a storm event, with P the rainfall depth [mm]; t_{Pg} the time of centre of gravity of a rainfall event [hours]; t_{Qmax} the time of peak flow [hours]; R the streamflow depth [mm]; S the stormflow depth [mm]; B the baseflow depth [mm]; Q_{max} the peak flow [10^{-3} m^3 s^{-1}]; Q_R the streamflow [10^{-3} m^3 s^{-1}]; $Q_{S\ i}$ the discharge at the onset of storm runoff conditions [10^{-3} m^3 s^{-1}]; $Q_{S\ f}$ the discharge at the end of storm runoff conditions [10^{-3} m^3 s^{-1}]; Q_B the baseflow [10^{-3} m^3 s^{-1}]; z_{SA} the depth of the water table in shallow aquifer below ground level [m]; $z_{SA\ i}$ the initial depth of the water table in shallow aquifer below ground level [m]; $z_{SA\ min}$ the minimum depth of the water table in shallow aquifer below ground level [m]; z_{DA} the depth of the water table in deep aquifer below ground level [m]

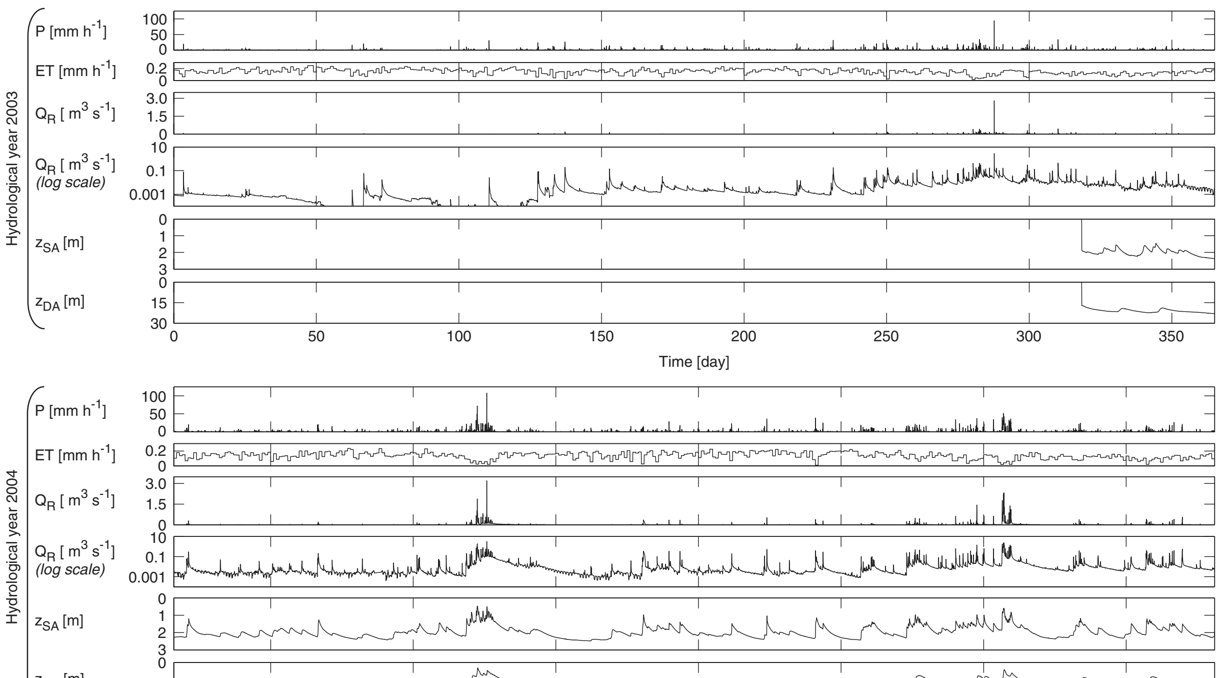

Figure 5. Hydrological time series for years 2003 (01/02/2003 to 31/01/2004) and 2004 (01/02/2004 to 31/01/2005), from top to bottom: P rainfall, ET evapotranspiration, Q_R discharge on a linear scale, Q_R discharge on a log scale, z_{SA} depth to shallow water table, and z_{DA} depth to deep water table

DOI: 10.1002/hyp

MAIN HYDROLOGICAL PROCESSES

Annual water balance

On an annual scale, outflows of the system (O_{DA}) represent the main term of the water balance (Equations (2) and (3)). As shown in Table II and in the hydrological behaviour scheme of the Féfé catchment (Figure 6), in 2003, O_{DA} accounted for 42% of the total annual rainfall, evapotranspiration (ET) 31%, and streamflow (R) 27%; in R, the baseflow component (B) was 1·7-fold higher than the stormflow component (S). However, in 2004, O_{DA} was 36%, ET 17%, and R 47%, so R was the main water balance component, and S was 6·1% higher than B. At Féfé, the annual rainfall was 4229 mm in 2003 and 7030 mm in 2004. A comparison of this annual rainfall pattern at Féfé with that recorded at the Neufchâteau meteorological station indicated that 2003 was close to the average year and 2004 was the rainiest in the last 53 years (Météo-France, 2005). Hence, when the annual rainfall increased 1·6-fold (between 2003 and 2004), S/P increased 2·4-fold. In the two cases, the total outflows for the shallow aquifer ($ET + B + D$) represented 90 and 76% of the water balance, respectively.

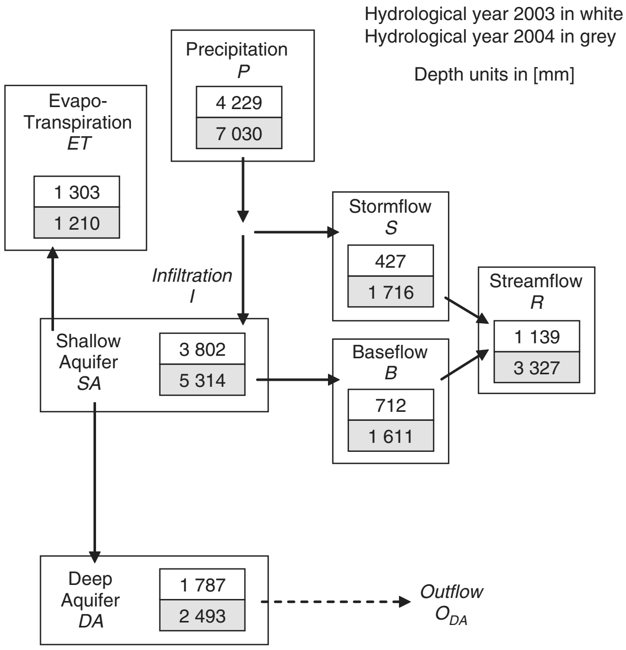

Figure 6. Hydrological behaviour scheme of the Féfé catchment

Impact of antecedent moisture conditions on hydrological processes

The variability of the hydrological series depended partly on antecedent moisture condition. Figure 5 shows that peaks of rainfall, peaks of streamflow, and peaks of shallow and deep water tables are simultaneous at daily time steps. This highlights that the surface and underground processes varied almost concomitantly, so transfers were rapid. Partitioning into different hydrological periods (DRY, TRANS, and WET) showed that the variability of hourly rainfall and hourly streamflow increased between DRY and WET periods (standard deviation varied from 1·7 to 9 mm and from 0·15 to 0·269 $m^3\ s^{-1}$ respectively—Table III), whereas such a gradient was not observed for the variability of water table depths and evapotranspiration.

The catchment response differed during the three periods DRY, TRANS, and WET. Comparing DRY and WET periods (Table IV), it is observed that S/P was 7·2-fold higher during the WET period. This increase in S/P was in line with the higher mean hourly streamflow, which was 33-fold higher in the WET periods. Consequently, during the WET period, stormflow became the main term of the water balance. The catchment response during the TRANS period is intermediate between DRY and WET.

Table II. Water balance of Féfé catchment on an annual scale in 2003 and 2004; Equations (2) and (3): $O_{DA} = D = P - ET - R$ with $R = S + B$

	2003	2004
Rainfall P (mm)	4 229	7 030
Evapotranspiration ET (mm)	1 303	1 210
Streamflow R (mm)	1 139	3 327
Outflows of the system O_{DA} (mm)	1 787	2 493
Storm flow S (mm)	427	1 716
Base flow B (mm)	712	1 611
R/P (%)	*24·6*	*43·2*
S/P (%)	*9·2*	*22·3*

Table III. Hydrological characteristics of the three antecedent moisture condition periods: minimum (min), maximum (max), mean (mean), and standard deviation (σ)

Characteristics of time series	Antecedent moisture condition periods											
	DRY				TRANS				WET			
	min	max	mean	σ	min	max	mean	σ	min	max	mean	σ
Hourly rainfall (mm)	0·0	38·5	0·4	1·7	0·0	34·2	0·8	2·6	0·0	107·9	3·3	9·0
Daily evapotranspiration (mm)	0·3	5·9	3·7	1·0	0·4	5·1	3·0	0·9	0·5	4·4	2·1	1·2
Hourly streamflow ($m^3\ s^{-1}$)	0·0	0·523	0·003	0·015	0·003	0·636	0·017	0·035	0·020	3·203	0·121	0·269
Water table depth of shallow aquifer z_{SA} (m)	1·0	2·5	2·1	2·1	0·8	2·4	1·8	0·2	0·5	1·9	1·4	0·3
Water table depth of deep aquifer z_{DA} (m)	12·6	25·6	22·1	2·5	9·4	24·0	16·7	3·6	3·9	14·8	10·2	2·4

DOI: 10.1002/hyp

Table IV. Water balance according to the antecedent moisture condition: dry (DRY), transitional (TRANS), and wet (WET)

	Antecedent moisture condition periods		
	DRY	TRANS	WET
Number of days	505	190	36
Rainfall P (mm)	4 856	3 520	2 883
Evapotranspiration ET (mm)	1 879	550	84
Streamflow R (mm)	859	1 548	2 059
Stock variation of the shallow aquifer and recharge of the deep aquifer $\Delta W_{SA} + D$ (mm)	2 118	1 422	740
Storm flow S (mm)	303	556	1284
Base flow B (mm)	556	992	775
R/P (%)	*17·7*	*44·0*	*71·4*
S/P (%)	*6·2*	*15·8*	*44·5*

Relations between water compartments at the storm event scale

Rainfall and stormflow. On a storm-event scale, the plot of P versus S (Figure 7a) shows an increase in the stormflow rate as rainfall increased. Excluding the five exceptional rainfall events of over 110 mm that occurred in the WET period, Figure 7b demonstrates that stormflow depth increases with increase in rainfall, and also with antecedent moisture condition, which is reaching saturation. Moreover, concerning the 66 flash storm events, the mean S/P for DRY, TRANS, and WET were 6·2%, 15·4%, and 24·4%, respectively, while the mean response time also dropped by 43 min, 31 min, and 22 min.

Infiltration and rise of the shallow water table. In Figure 8, the plot of infiltration versus recharge of the shallow aquifer was established from 36 flash events for which ET was insignificant relative to the water volumes involved. Infiltration depth was defined as follows:

$$I = P - S \tag{5}$$

The rise of the water table starts at around 8 mm of infiltration, suggesting a store in the vadose zone. One surprising observation in this plot is that the antecedent moisture condition revealed by the three (DRY, TRANS, and WET) periods had no effect on the recharge. A chi-square test has been carried out to test the null hypothesis, which states that there is no effect of antecedent soil moisture on infiltration depth. With a distribution of four classes for infiltration depth and three classes of soil moisture, results of the test showed that the corresponding probability was around 0·5, meaning that we cannot reject this null hypothesis. Concerning the outlier in the TRANS conditions (coordinate $I = 25{\cdot}7$ mm and $dz_{SA} = 726{\cdot}5$ mm, Figure 8), it occurs for a high rainfall event ($P = 35$ mm, $S/P = 25\%$), generating high runoff and infiltration depth. Finally, a rainfall intensity parameter was introduced as an explaining factor, but results were not conclusive.

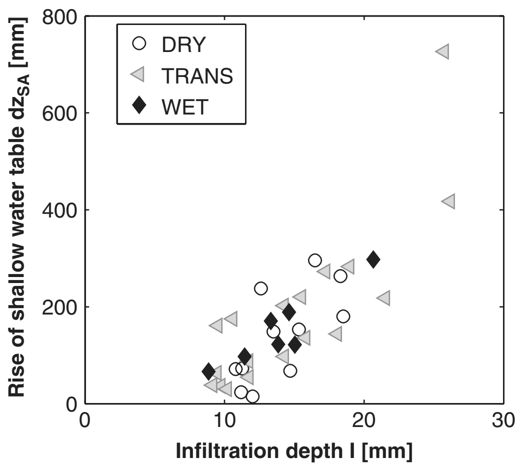

Figure 8. Recharge of the shallow aquifer by infiltration

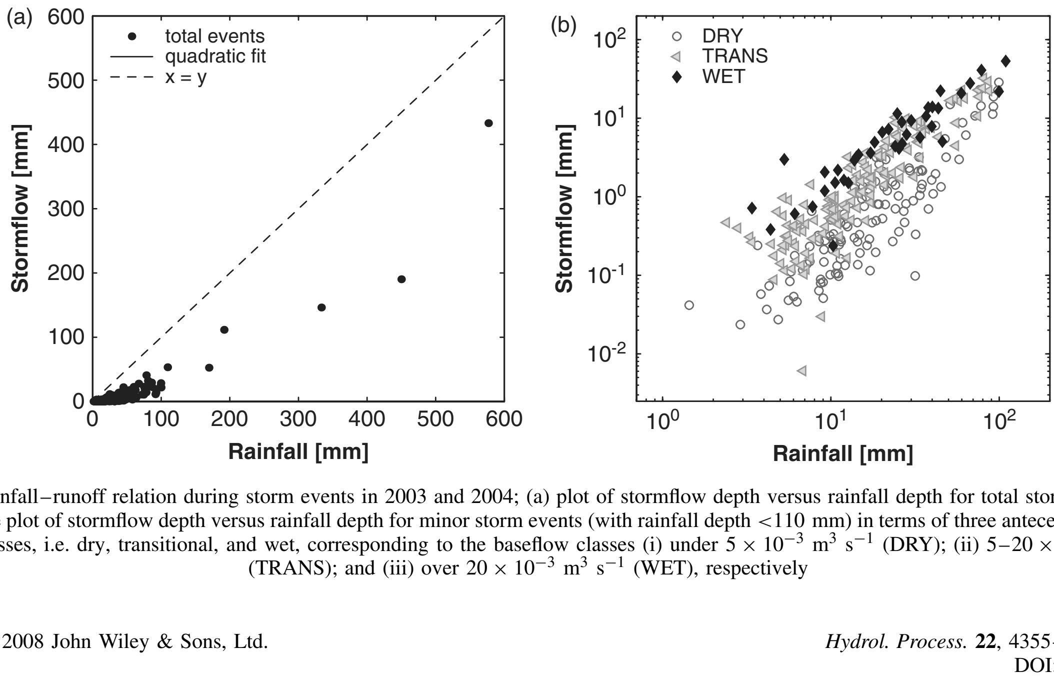

Figure 7. Rainfall–runoff relation during storm events in 2003 and 2004; (a) plot of stormflow depth versus rainfall depth for total storm events; (b) log–log scale plot of stormflow depth versus rainfall depth for minor storm events (with rainfall depth <110 mm) in terms of three antecedent moisture condition classes, i.e. dry, transitional, and wet, corresponding to the baseflow classes (i) under 5×10^{-3} m^3 s^{-1} (DRY); (ii) 5–20 $\times 10^{-3}$ m^3 s^{-1} (TRANS); and (iii) over 20×10^{-3} m^3 s^{-1} (WET), respectively

One explanation for this process is that there is a constant infiltration capacity with depth in the vadose zone. In fact, in a permanent humid context, the initial soil moisture is always close to saturation even if storm events occur in DRY period. No decrease was observed of the saturated hydraulic conductivity with depth; the geometric means of Ks in the surface organic horizon and the weathered horizon, which accounted for over half of the shallow aquifer, were 28·2 and 39·1 mm h^{-1}, respectively, with a standard deviation of 100·4 and 38·0. These values were in agreement with the rapid transfers noted during the rise of the shallow water table (Figures 3 and 4).

Shallow water table and baseflow. For the 36 flash storm events, an exponential relation was adjusted (Figure 9, Equation (6)) between the initial discharge before stormflow $Q_{S\ i}$ and the shallow water depth $z_{SA\ i}$.

$$Q_{S\ i} = 1048{\cdot}9 \exp(-2{\cdot}62\ z_{SA\ i}) \quad (r^2 = 0{\cdot}77) \qquad (6)$$

with $Q_{S\ i}$ in [10^{-3} m^3 s^{-1}] and $z_{SA\ i}$ in [m]. $Q_{S\ i}$ is the baseflow at the beginning of the storm event and thus is just the result of a shallow aquifer drainage process. Note that the streamflow hydrograph separation method used here assumes that Q_B increases during storm events (Figure 4). This increase was in line with the increase of the shallow water table due to the infiltration process.

Discussion

Hydrological behaviour of the catchment. Underground outflows from the shallow aquifer, which is drained by the stream, prevailed over streamflow (42% and 27% of the annual rainfall, respectively). This was surprising in comparison with other similar-sized catchments in highly permeable soils (Table V), 0 to 1·5% and 41·0 to 74·1%, respectively, for the four tropical catchments Kali Mondo (Bruijnzeel, 1983), Lake Calado (Lesack, 1993), Cunha Forest (Fujieda *et al*., 1997) and Lutz Creek (Kinner and Stallard, 2004). Details of the lithological framework in depth are not available for all these studies, but the quasi-absence of outflows means that there is, in all cases, an impervious material, which hinders deep percolation from the superficial formation. In the case of the Féfé catchment, the low streamflow component could be explained by the absence of a significantly impervious layer hindering vertical underground outflows from the shallow aquifer and by a geometrical configuration of volcanic deposits allowing drainage of the deeper aquifer below the gauging station.

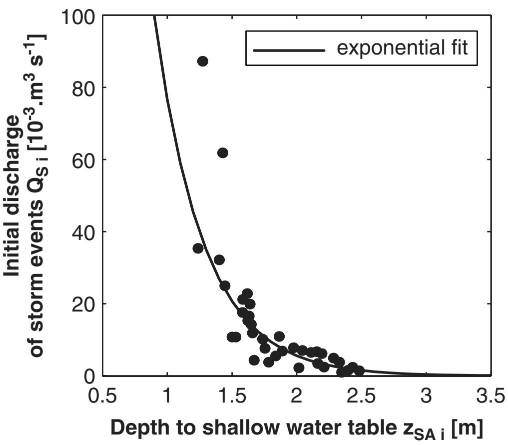

Figure 9. Drainage of the shallow aquifer by the catchment stream (exponential fit: $r^2 = 0{\cdot}77$)

Few previous studies have reported the presence of two overlapping aquifers, despite the fact that this configuration is quite common in various settings, as discussed by Join *et al*. (1997) concerning Réunion Island. It could be assumed that this type of hydrosystem is common in volcanic environments because Lachassagne (2006) suggested that pumiceous lapillis or tuff deposits (which encompass the shallow aquifer at Féfé) form superficial compartments that contribute to the drainage system in head catchments, and that nuees ardentes deposits (which encompass a part of the deep aquifer at Féfé) are conductive and correspond to potentially permeable aquifers with a large water storage capacity.

The annual evapotranspiration depth was around 1300 mm, which is comparable with the depth recorded in tropical rainforest catchments presented in Table V. It is also comparable with the depth recorded by Van Vosselen *et al*. (2005), at a tropical site in Surinam with banana crop cover (1168 mm year^{-1}). This study also noted that a depth of 1460 mm year^{-1} is realistic in well-watered conditions resembling the very humid conditions at Féfé.

Hydrological processes. The stormflow coefficients S/P increased with rainfall and with antecedent moisture conditions. The annual 10% S/P at Féfé was comparable with that of previous studies at Kali Mondo (5%), Lake Calado (3%), Cunha Forest (11%), and Lutz Creek (10%) (Table V). On a storm-event scale at Féfé, S/P ranged from 6·2% to 24·4% between the DRY and WET periods. These values were in the same range as in rainforest catchments such as at Palma in Dominica (Walsh, 1980), Bisley II in Porto Rico (Schellekens *et al*., 2004), and South Creek in Australia (Bonell *et al*., 1981) where SSSF and SOF are predominant, but were up to 4-fold higher than in the catchment of Lake Calado where channel precipitation (CP) associated with SOF from areas immediately adjacent is the major process. Note that the Kali Mondo catchment is in an intermediate hydrological setting since Bruijnzeel (1983) observed that processes of SSSF, HOF, CP, and SOF occurred depending on location in the basin. Nevertheless, at Féfé, SSSF was also unlikely since the Ks measurements did not show a substantial drop in the deep infiltration capacity of Andosol, contrary to the observation of a shallow impeding layer in many tropical sites reported in Table V. Moreover, in banana plantations located in mountainous areas in Guadeloupe, cropping practices are only manual. Without mechanized tillage operations, which introduce a compaction effect of the soil at a 30–40 cm depth, lateral subsurface flow is limited in favour of vertical infiltration.

Table V. Comparison of annual water balance characteristics and main hydrological processes from the present study with those from previous studies at small humid tropical catchment sites with highly permeable soils

Sites	Area	Vegetation	Soil[a]	Mean *Ks* of the surface horizon	Shallow impeding layer	P^b	*ET/P*	R/P	$\Delta W/P$	D/P	Main stormflow processes[c] and size of contributing areas in brackets	Annual S/P^d	Event S/P^d	Authors
	(ha)	(–)	(–)	(mm h^{-1})	(–)	(mm)	(%)	(%)	(%)	(%)		(%)	(%)	(–)
Guadeloupe (Féfé)	17·8	Banana plantations	Andosol	28	No	4 229	30·8	26·9	0	42·3	HOF from banana fields (<20%), HOF from roads and sheds (5%), CP (0·6%)	10·1	6·2–24·4	This article
Indonesia (Kali Mondo)	19·0	Agathis plantations	Andosol	955	Depending location	4 668	26·1	74·1	−0·2	0	SSSF (<7·7%), HOF from trails and yards (0·88%), CP (1·3%)	4·7	1·7–8·0	(Bruijnzeel, 1983)
Brazil (Lake Calado)	23·4	Tropical rainforest	Ferralsol	≈54	No	2 870	39·0	57·5	2·0	1·5	CP (≈4%)	3·0	0·5–4·0	(Lesack, 1993)
Brazil (Cunha Forest)	56·0	Tropical rainforest	Ferralsol	≈36	Yes	2 319	30·0	70·0	0	0	SSSF from hillslopes (6%) and SOF from wet riparian areas (5%)	11·0	/	(Fujieda *et al.*, 1997)
Panama (Lutz Creek)	9·7	Tropical rainforest	Acrisol	30–66	Yes	2 400	52·0	41·0	7·0	0	SSSF and SOF	10·0	/	(Godsey *et al.*, 2004; Kinner and Stallard, 2004)
Australia (South Creek)	25·7	Tropical rainforest	Acrisol	>800	Yes	4 175	/	/	/	/	SSSF from hillslopes and SOF	/	45·0–74·0	(Bonell, 1993; Bonell and Gilmour, 1978; Bonell *et al.*, 1981)
Porto Rico (Bisley II)	6·4	Tropical rainforest	Acrisol	260	Yes	3 530	31·0	/	/	/	SSSF and SOF	/	1·0–28·0	(Schellekens *et al.*, 2004)
Peru (La Cuenca)	0·75	Tropical rainforest	Acrisol	300	Yes	3 300	/	/	/	/	SSSF	/	/	(Elsenbeer and Vertessy, 2000; Vertessy and Elsenbeer, 1999)
Dominique (Palma)	122·0	Tropical rainforest	Ferralsol	250	Yes	5 432	/	/	/	/	SSSF	/	32·0 (max.)	(Walsh, 1980)

[a] According WRB (2006).
[b] Water balance adapted from Equation (2): $D = P - ET - R - \Delta W$; rainfall ($P$), evapotranspiration ($ET$), streamflow ($R$), water storage ($\Delta W$), outflows of the shallow aquifer (D).
[c] Horton Overland flow (HOF); Saturation Overland Flow (SOF); Channel Precipitation (CP) associated with SOF from areas immediately adjacent to the stream channel; SubSurface StormFlow (SSSF).
[d] S/P = stormflow coefficient.

In this setting, the values of event S/P related to the antecedent moisture condition at the catchment scale could be explained by two possible processes: SOF and/or HOF. However, according to spatial observations in the catchment and experimental results in a similar context, one can characterize the occurrence of these two processes. First, SOF on hillslopes and flat areas seemed to be unlikely as indicated by the upstream and downstream piezometric time series, which showed that the shallow water table never rose to the surface horizon even for exceptional storm events in May and November 2004. Second, HOF is promoted here for several reasons: (i) via a stemflow process, rainfall was concentrated at the base of banana plants, generating overland flow at the plant scale (Cattan *et al.*, 2007) and increasing S/P significantly at both the plot and catchment scale (Charlier *et al.*, 2007); (ii) farmers created less permeable areas such as roads and platforms and impermeable areas such as sheds where overland flow occurs; (iii) close to Féfé at the Neufchâteau station in a banana field (3000 m^2) on permeable Andosol (mean $Ks = 75$ mm h^{-1}), S/P can reach 35% (Cattan *et al.*, 2006); and (iv) in the literature, some studies in cultivated areas have reported the prevalence of HOF during storm events in humid tropics (Fritsch, 1992; Ziegler *et al.*, 2004; Zimmermann *et al.*, 2006). Hence, during storm events, HOF seemed to prevail over other processes at Féfé catchment. The size of contributing areas can be calculated as follows: HOF from less permeable areas (farm roads and platforms) associated with overland flow from impermeable areas (sheds) and CP from the stream and the pool represented, respectively, 5·0 and 0·6% of the total basin. The total contributing area of these two processes (5·6%) can explain the major part of the minimum S/P at the event scale (6·2% in DRY period). It means that for rainy events, HOF from banana fields is producing up to 20% of S/P. These last results were out of line with the tropical forest catchment data presented in Table V. In these latter catchments, SSSF, SOF, and CP were the most common stormflow processes, while HOF occurring locally on the hillslopes had a very minor impact at the outlet of the catchment. This can be due to higher saturated hydraulic conductivity on the surface horizon (up to 955 mm h^{-1}; see Table V).

At the event scale at Féfé, the stormflow coefficient S/P is related partly to soil storage capacity, as describe in numerous tropical small catchments (Dubreuil, 1985; Chevallier and Planchon, 1993). This type of relation was not, however, observed at Kali Mondo and Lake Calado where S/P events were less than 8%. An explanation may be the absence of significant HOF from hillslopes and the absence of SOF on wetland areas in these two sites, and the prevalence of CP and SSSF, which are less affected by the water storage. In the current case, the significant effect of initial soil moisture at the catchment scale is generated by a low variation of the water storage on porous Andosols permanently closed to saturation in a humid tropical climate (Dorel *et al.*, 2000).

Infiltration was related to the recharge of the shallow aquifer. Rapid recharge was shown by the synchronization between the onset of the water table rise and flood onset (Figures 3 and 4). Schellekens *et al.* (2004) also noted at the Bisley II catchment, an instantaneous response of the piezometers, which they explained by short-circuit flow through macropores. At Féfé, this extent of macroporosity was found in volcanic materials of the superficial formation described in the *study site* section.

Modelling constraints. The catchment behaviour scheme (Figure 6) summarizes water flows from each compartment involved and transfer processes that link them. In order to verify the main hypothesis about the hydrological processes highlighted above, a modelling approach is presented in the next section. The experimental step was conducted at the catchment scale, and thus a lumped approach was chosen for the modelling step. In spite of good performance by lumped models (Perrin *et al.*, 2001), their applications to water resource engineering have promoted discharge simulation and hence disregarded water table simulation. Consequently, to account for piezometric fluctuations in the two overlapping aquifers at Féfé, an original model was needed, adapted to the overall framework of the study (Figure 10). The constraints were: (i) to equally represent surface and underground transfers; (ii) to integrate two groundwater systems; and (iii) to accurately simulate the annual water balance, flooding, and water table fluctuations for WET periods.

CONCEPTUAL LUMPED HYDROLOGICAL MODEL

Model structure

Since the 1960s, lumped conceptual rainfall–runoff models have been used in hydrology (Crawford and

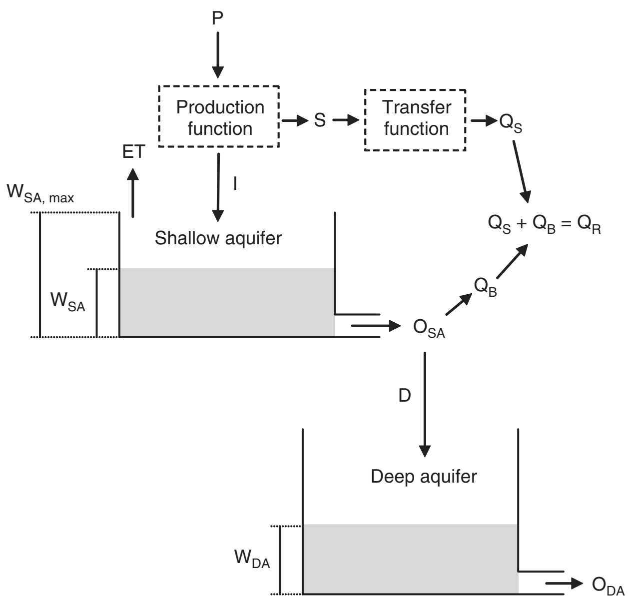

Figure 10. Structure of the conceptual lumped model built specifically to the Féfé catchment

Linsley, 1966; Bergström, 1995; Donigan *et al.*, 1995; Edijatno *et al.*, 1999; Perrin *et al.*, 2003). These models consider the catchment as an undivided entity, and use lumped values of input variables and parameters. For the most part (for a review see Singh, 1995), they have a conceptual structure based on the interaction between storage elements representing the different processes with mathematical functions to describe the fluxes between the stores. In this study, a model was built to simulate the Féfé catchment's main observed hydrological processes, integrating streamflow with fluctuations in the two overlapping aquifers (Figure 10). The modelling approach followed herein will be lumped at the scale of the catchment, which will be considered as one entity. A two-aquifer-layer model was developed. The first layer, denoted as 'shallow aquifer', controls stormflow, infiltration, baseflow, and recharge of the deep aquifer. The second layer, denoted as 'deep aquifer', represents the aquifer where outflows of the system occur. Relationships between the shallow aquifer and stream were based on Equation (6). For modelling, the equation is fitted with events from the calibration period only, in order to have independent calibration and validation. Then, a unit hydrograph transfer function was used to route storm flows to the outlet. The outputs of the model were a simulated hydrograph and two shallow and deep simulated piezometers, which were compared, respectively, with the original measured hydrographs, z_{SA} and z_{DA}, to assess model performance. A general description of each procedure is given below.

The production function. A constant threshold separates the rainfall P into rainfall excess or stormflow S, and infiltration I. Since Atlantic rain-bearing winds bring permanently high rainfall, there is a state of water close to saturation throughout the entire year. Thus, the simple production function used is controlled by the Ks threshold; in this model, the variability of S/P depends directly on the variability of rainfall intensity. The two outputs I and S depend on the Ks parameter and on the value of the input P at a 2 min time step according to the following equations:

$$\text{If } P < Ks \quad \text{then} \quad I = P \text{ and } S = 0 \tag{7}$$

$$\text{If } P > Ks \quad \text{then} \quad I = Ks \text{ and } S = P - Ks \tag{8}$$

The shallow aquifer. The shallow aquifer element has one input, I, and two outputs, the evapotranspiration ET and the outflow O_{SA} [LT^{-1}]. ET is calculated according to Equation (1), and O_{SA} is a calculated function of the aquifer stock W_{SA} using a linear relation

$$O_{SA} = k_{SA} W_{SA} \tag{9}$$

where k_{SA} [T^{-1}] is a constant characterizing the recession curve of the shallow aquifer. The value of the water store variable W_{SA} of the shallow aquifer is obtained using the continuity equation

$$\frac{dW_{SA}}{dt} = I(t) - ET(t) - O_{SA}(t) \tag{10}$$

The water level of the shallow aquifer h_{SA} is assume to be proportional to W_{SA} and is calculated as follows:

$$h_{SA} = W_{SA}/n_{SA} \tag{11}$$

where n_{SA} [−] is a parameter representing the effective porosity of the shallow aquifer.

The shallow aquifer layer has a maximum thickness $h_{SA,\ max}$ equal to the 6 m height of the weathered pumiceous lapillis formation (Figure 3); the maximum storage depth $W_{SA,\ max}$ is thus equal to $h_{SA,\ \max} \times n_{SA}$. At a time step, if W_{SA} is superior to $W_{SA,\ max}$, then the overflow ($W_{SA} - W_{SA,\ max}$) is added to stormflow S.

O_{SA} represents two flow pathways, the lateral baseflow B and the vertical recharge of the deep aquifer D. Baseflow discharge Q_B is calculated function from Equation (6) fitted to calibration events ($Q_B = Q_{S\ i} = 833{\cdot}8\ \exp(-2{\cdot}43 z_{SA\ i})$), and the recharge of the deep aquifer (D) is deduced from the difference between O_{SA} and B:

$$D = O_{SA} - B \quad \text{with } B = Q_B/A \tag{12}$$

where B [L] the baseflow depth and A [L^2] the catchment area.

The deep aquifer. The deep aquifer has one input, D, and one output, the outflow O_{DA} [LT^{-1}]. O_{DA} is calculated as a function of the aquifer stock W_{DA} using a linear relation

$$O_{DA} = k_{DA} W_{DA} \tag{13}$$

where k_{DA} [T^{-1}] is a constant characterizing the recession curve of the deep aquifer. The deep aquifer layer has a maximum thickness $h_{DA,\ max}$ equal to the 30 m mean height estimated for the nuees ardentes (associated with andesitic lava flows) formation (Figure 3). In order to reduce the number of parameters, the deep aquifer does not have a maximum storage depth. The value of the water store variable W_{DA} of the deep aquifer is obtained using the continuity equation

$$\frac{dW_{DA}}{dt} = D(t) - O_{DA}(t) \tag{14}$$

The water level of the deep aquifer h_{DA} is assumed to be proportional to W_{DA} and is calculated as follows:

$$h_{DA} = W_{DA}/n_{DA} \tag{15}$$

where n_{DA} [−] is a parameter representing the effective porosity of the deep aquifer.

The transfer function. A transfer function is used to route the rainfall excess S to the outlet of the catchment. A unit hydrograph linear model, based on a Hayami (1951) kernel function, which is a resolution of the diffusive wave equation, was used to simulate the transfer (Moussa and Bocquillon, 1996). Let $A.S(t)$ [L^{3}T^{-1}] be the input hydrograph and $Q_S(t)$ the routed storm flow hydrograph at the outlet:

$$Q_S(t) = \int_0^t A.S(\tau).H(t-\tau).d\tau \quad \text{with}$$

$$H(t) = \left(\frac{\omega.z}{\pi}\right)^{\frac{1}{2}} . \frac{\exp^{z\left(2-\frac{t}{\omega}-\frac{\omega}{t}\right)}}{(t)^{3/2}} \qquad (16)$$

where $H(t)$ the Hayami kernel function, ω [T] is a time parameter that represents the centre of gravity of the unit hydrograph, z [dimensionless] a form parameter, $\pi = 3{\cdot}1416$, and t the time [T]. The two parameters are ω and z. The total streamflow discharge at the outlet Q_R is calculated from the sum $Q_R = Q_S + Q_B$.

Model properties and parameters. The input rainfall P is usually given as a function of time in the form of a histogram using a fixed time interval. Consequently, the other variables are also presented as functions of time, and the computations are carried out for the same fixed time interval. The Ks parameter of the production function is not calibrated; Ks was taken as constant and equal to the geometric mean of field measurement values ($Ks = 28{\cdot}2$ mm h^{-1}). The model needs six calibration parameters: (i) four parameters for aquifers, the two constants characterizing the recession curve k_{SA} and k_{DA} and the two effective porosities n_{SA} and n_{DA} of the shallow and the deep aquifer, and (ii) two parameters for the transfer function, the lag time ω and the shape parameter z. The two initial conditions for aquifer levels are measured data $h_{SA,i}$ and $h_{DA,i}$ at $t = 0$. The outputs are the calculated streamflow discharge $Q_R(t)$, the water table depth of the shallow aquifer $z_{SA}(t)$ (with $z_{SA} = h_{SA,\ max} - h_{SA}$) and the water table depth of the deep aquifer $z_{DA}(t)$ (with $z_{DA} = h_{DA,\ max} - h_{DA}$). In the simulation, the calculated $Q_R(t)$, $z_{SA}(t)$, and $z_{DA}(t)$ are compared with the measured values of streamflow discharge $Q_R(t)$, of water table depths $z_{SA}(t)$ and $z_{DA}(t)$, respectively (Figure 11).

Calibration strategy

The model runs on a 2 min time step. The modelling period does not include the year 2003 when there were no automatic records of water levels in piezometers. Apart from this, no account was taken of variation in cultural practices and in the growing states of banana plants during the validation period, for reasons which can be related to features of banana growth. At the plant scale, at the end of fruit growth, the bunch is harvested, the pseudostem is cut down, and one sucker, previously selected, is allowed to grow, starting a new cycle. Thus, two successive crop cycles slightly overlap. Several crop cycles are cultivated successively regardless of the seasons. At the plot scale, since all plants do not grow at the same speed, there is a gap between the growth states of banana plants. This gap increases with the number of crop cycles. As a consequence, 2 years after planting, many of the growing stages coexist in a banana plantation, leading, on average, to a permanent and homogeneous cover (Tixier *et al.*, 2004). Consequently, neither the cultural practices nor the average state of growth of banana plants at the plot scale depend on the seasons. Thereby, it is assumed for this lumped approach that there is a negligible seasonal effect of cropping practices and of growth state on hydrological processes during a period of one year. The calibration period was from August 2004 to January 2005, while the validation period was from January 2004 to July 2004. Each of these periods included a WET and a DRY period. The optimization of parameters was carried out according to the following criteria given by order of use during the calibration procedure: the Nash and Sutcliffe coefficient (1970) on Q_R, $\log(Q_R)$, z_{SA}, and z_{DA}, noted respectively as $NS\ Q_R$, $NS\ \log(Q_R)$, $NS\ z_{SA}$, and $NS\ z_{DA}$; parameters were optimized manually to obtain a maximal value of these criteria. To assess performances of the model, these four NS criteria were used and, in addition, differences between measured and simulated $Q_{\max}$, S/P, and V_R. The following values were obtained for an optimal calibration: $k_{SA} = 2{\cdot}4\mathrm{e}^{-6}$ s^{-1}, $k_{DA} = 2{\cdot}1$ e^{-6} s^{-1}, $n_{SA} = 0{\cdot}079$, $n_{DA} = 0{\cdot}017$, $\omega = 26{\cdot}1$ min, and $z = 1{\cdot}3$. A sensitivity analysis of the Ks, k_{SA}, and k_{DA} parameters was performed during the calibration period and a summary of the calibration and validation results is given in Table VI.

Sensitivity analysis

The sensitivity analysis focused on the Ks, k_{SA}, and k_{DA} parameters. Differences of ±25% around the means were tested. A Ks variation of +25% and −25% led to a loss of 5 to 10 percentage points, respectively, in discharge

Table VI. Model calibration and validation results; computing interval is 2 min and calculation interval of calibration and validation criterion is 1 h. Notation: S/P the stormflow coefficient, $NS\ Q_R$, $NS\ \log(Q_R)$, $NS\ z_{SA}$ and $NS\ z_{DA}$, respectively the Nash and Sutcliffe coefficient of stream discharge, of (base 10) logarithm of stream discharge, of water depth of the shallow aquifer, and of water depth of the deep aquifer

Simulation period	Calibration (August 2004–January 2005)	Validation (January–July 2004)
Rainfall (mm)	3 868	3 470
Duration (month)	6	6
Measured maximum discharge (m^3 s^{-1})	2·3	3·2
Calculated maximum discharge (m^3 s^{-1})	1·6	3·9
Calculated S/P (%) with the straight line method	26·3	16·2
Calculated S/P (%) with the conceptual lumped model	21·2	19·2
Measured streamflow volume (m^3)	357 000	252 000
Calculated streamflow volume (m^3)	342 000	306 000
$NS\ Q_R$ (−)	0·80	0·88
$NS\ \log(Q_R)$ (−)	0·61	0·32
$NS\ z_{SA}$ (−)	0·88	0·86
$NS\ z_{DA}$ (−)	0·72	0·56

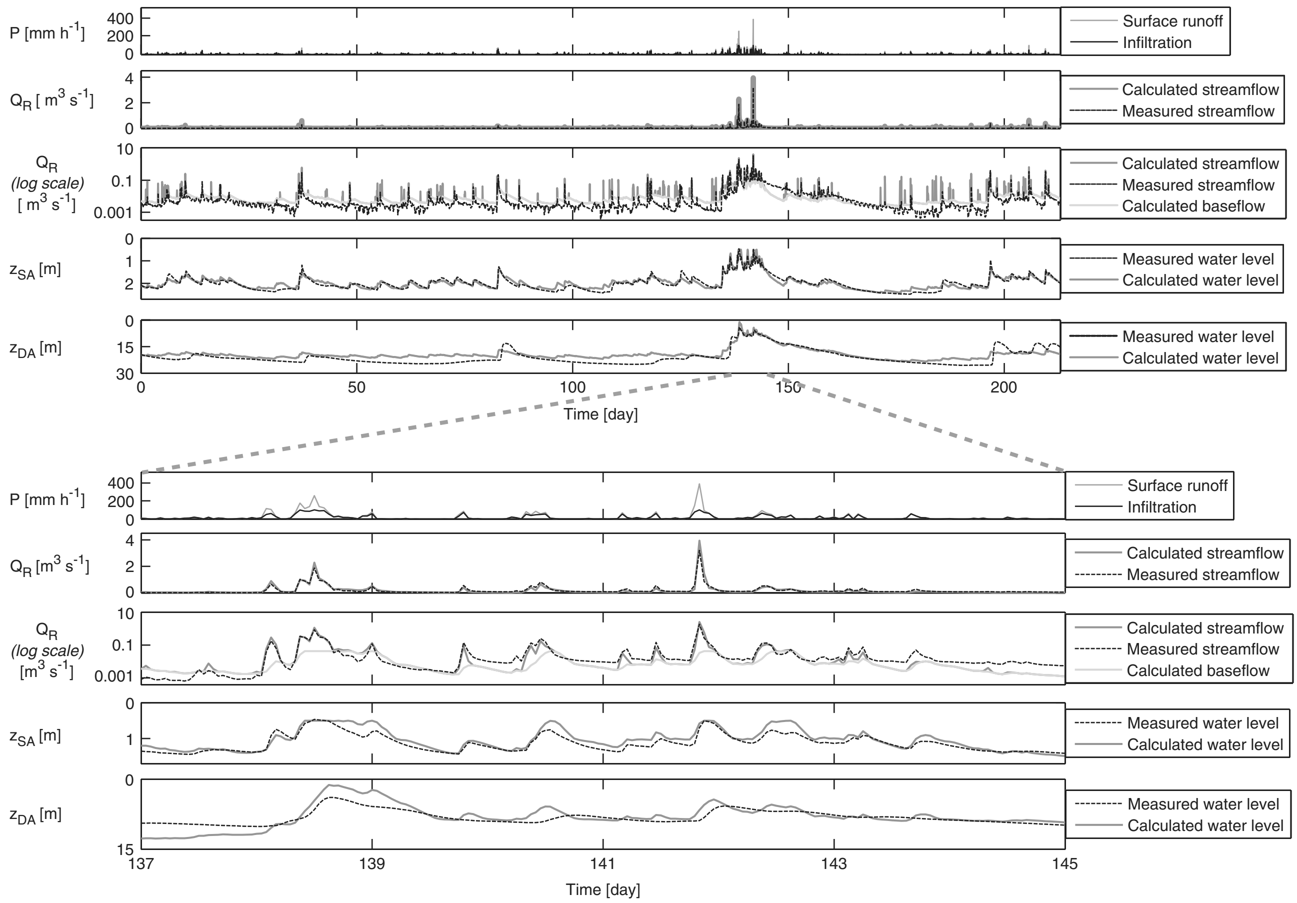

Figure 11. Simulation results on hydrograph and water levels in shallow and deep aquifers during the entire validation period (upper graph: from 01/01/2004 to 31/07/2005) including the extreme rainfall event in May 2004 (lower graph: from 17/05/2004 to 25/05/2004) - from top to bottom: P rainfall, Q_R discharge, z_{SA} water depth of the shallow aquifer, and z_{DA} water depth of the deep aquifer

representation quality (*NS* Q_R criterion), and generated a variation of S/P ranging from 15 to 30%, respectively; the same k_{SA} variation led to a rise of 4 percentage points and a loss of 13 percentage points in low discharge representation quality (*NS* $log(Q_R)$ criterion) and a rise of 1 percentage point and a loss of 22 percentage points in the water depth of the shallow aquifer z_{SA} (*NS* z_{SA} criterion); for k_{DA}, the impact on the water depth of the deep aquifer was highest and led to a loss of 6 to 31 percentage points (*NS* z_{DA} criterion). As expected, the streamflow was highly sensitive to *Ks* parameter variations and the simulation quality for aquifer levels were most sensitive to the parameters of the aquifer recession curves. However, discharges were relatively insensitive to variations in these parameters.

Calibration and validation

The results of the calibration and validation are given in Table VI. Performances of the model were mitigated for surface transfers and satisfactory for underground transfers (Figure 11). The accurate simulation of high flooding ($NS\ QR = 0{\cdot}80$ during calibration and 0·88 during validation) supported the hypothesis that HOF is a main process for wet periods. Poor simulation of low flooding ($NS\ \log(QR) = 0{\cdot}61$ during calibration and 0·32 during validation) could be explained by three factors: (i) a fair simulation of the baseflow in WET periods due to a less satisfactory adjustment of Equation (6) for high events in the calibration period; (ii) an overestimation of low flood events in DRY periods since the model did not take into account the influence of the antecedent moisture condition for runoff (which was demonstrated experimentally); and (iii) a significant change of land uses in the basin, which was neglected in the initial hypothesis for the calibration strategy. A good simulation of the shallow aquifer for DRY and WET periods ($NS\ z_{SA} = 0{\cdot}88$ during calibration and 0·86 during validation) was compatible with the *Ks* field data and verifies the hypothesis of a rapid recharge of the shallow aquifer due to high hydraulic conductivity of the Andosols on the whole height of the aquifer. Finally, the deep water table was not as well simulated ($NS\ z_{DA} = 0{\cdot}72$ during calibration and 0·56 during validation), probably due to influencing factors outside of the catchment, such as uphill inflows and lateral outflows of the system.

Domain and limits of application of the model

First, the main assets of the model are the parameterization simplicity within all six calibration parameters, including two for the transfer function and four parameters for aquifers. In contrast with most lumped models, this one enables the simulation of three variables:

discharge at the outlet, and water levels in a shallow and a deep piezometer. Moreover, good performance of the model in wet periods allows its use to overcome problems of missing data during heavy rainfall periods. The main fault of this approach is that it is developed using only one year of observations during the rainiest year since 1952. Consequently, the model, which is not adapted for flood events during dry periods (when antecedent moisture condition is marked), cannot be tested properly. Finally, the modelling approach is only valid for the Féfé catchment owing to the use of an empirical relation (Equation (6)), which is based on physical and geometrical characteristics of the catchment, and specific parameters such as the recession curve and effective porosity for aquifer simulations. Nevertheless, the principle of this simple modelling approach could be extended to other sites.

CONCLUSION

The aim of the study was to establish the hydrological behaviour of a small, cultivated tropical catchment and to develop a simple model to simulate the hydrograph and the aquifer levels simultaneously. This is an important issue that emphasizes the role of cultivated area on volcanic deposits in a humid tropical area that may lead to unusual surface and underground flow at the watershed scale.

For the hydrological behaviour of the catchment, one main unique feature is the predominance of underground outflows from the deep aquifer that prevailed over streamflow (42% and 27% of the annual rainfall, respectively). This could be explained by the particular framework of the deposits; the absence of a significantly impervious layer hindered vertical recharge of the deep aquifer from the shallow aquifer and a geometrical configuration allowed drainage of the deeper aquifer below the gauging station. As a consequence, the two aquifers are drained by different streams, inside and outside the Féfé catchment. These are important features to take into account in further studies which are aimed at assessing the environmental impact of agricultural practices or pollution.

For the hydrological processes, high stormflow coefficients were observed on a storm event scale. This was probably due to the fact that the catchment was cultivated and particularly, that banana plantations can enhance runoff at the local scale thanks to rainfall redistribution by the banana canopy (Cattan *et al*., 2007). This hydrological functioning of cultivated areas under high rainfall intensities, combined with the absence of a shallow impeding soil layer (which would promote SSSF), suggests that HOF from hillslopes could prevail over other processes. These results are in accordance with the literature regarding the effects of deforestation of the rainforest, and showed that the hydrodynamic features of cultivated areas have to be characterized.

Finally, an original lumped model with six calibration parameters was built on the behaviour scheme of Féfé. The results of the multi-criteria calibration and validation show fair to good agreement between measured and simulated variables and consequently, the model was consistent with the main hydrological processes observed from experimental results for wet conditions. However, different processes observed on another tropical volcanic catchment (Bruijnzeel, 1983; Walsh, 1980) and the lack of other studies in this context precludes any generalizations about hydrological behaviour of volcanic basins. In this setting, it appears that a geological and a hydrogeological survey are thus essential to identify flow paths in this complex framework.

ACKNOWLEDGEMENTS

We thank Germain Onapin for his active contribution to the field work. This study was funded by the Guadeloupe Region (FWI), the Ministère de l'Ecologie et du Développment Durable (France) and the European Community under the project 'Assessment of water-pollution risks associated with agriculture in the French West Indies: management at the catchment scale'.

REFERENCES

Bergström S. 1995. The HBV model. In *Computer Models of Watershed Hydrology*. Singh VPE (ed). Water Resources Publications: Colorado; 443–476.

Bonell M. 1993. Progress in the understanding of runoff generation dynamics in forests. *Journal of Hydrology* **150**(2–4): 217–275.

Bonell M, Gilmour DA. 1978. The development of overland flow in a tropical rainforest catchment. *Journal of Hydrology* **39**(3–4): 365–382.

Bonell M, Gilmour DA, Sinclair DF. 1981. Soil hydraulic properties and their effect on surface and subsurface water transfer in a tropical rainforest catchment. *Hydrological Sciences Bulletin* **26**(1): 1–18.

Boudon G, Dagain J, Semet MP, Westercamp D. 1987. Carte géologique 1 : 20 000 du massif volcanique de la Soufrière (Département de la Guadeloupe, Petites Antilles). BRGM, Paris.

Bouwer H. 1986. Intake rate: cylinder infiltrometer. In *Methods of Soil Analysis, Part 1. Physical and Mineralogical Properties, Monograph 9*. Klute A (ed). ASA: Madison, WI; 825–843.

Bruijnzeel LA. 1983. *Hydrological and biochemical aspects of man-made forests in South-Central Java, Indonesia*. PhD thesis; Free University of Amsterdam.

Bruijnzeel LA. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment* **104**(1): 185–228.

Buytaert W, Deckers J, Wyseure G. 2006. Description and classification of nonallophanic Andosols in south Ecuadorian alpine grasslands (paramo). *Geomorphology* **73**(3–4): 207–221.

Cattan P, Bussière F, Nouvellon A. 2007. Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation. *Hydrological Processes* **21**(16): 2196–2205.

Cattan P, Cabidoche Y-M, Lacas J-G, Voltz M. 2006. Effects of tillage and mulching on runoff under banana (Musa spp.) on a tropical Andosol. *Soil and Tillage research* **86**(1): 38–51.

Chaperon P, l'Hote Y, Vuillaume G. 1983. Les ressources en eau de surface de la Guadeloupe. *Cahiers ORSTOM, Série Hydrologie* **20**(3–4): 149–178.

Charlier JB, Moussa R, Cattan P, Voltz M. 2007. *Hydrological Modelling from the Plot to the Catchment Scales in a Tropical Cultivated Area.* European Geosciences Union: Vienna, Austria.

Chevallier P, Planchon O. 1993. Hydrological processes in a small humid savanna basin (Ivory Coast). *Journal of Hydrology* **151**(2–4): 173–191.

Chow VT, Maidment DR, Mays LW. 1988. *Applied Hydrology*. McGraw-Hill International Editions: New York.

Colmet-Daage F. 1969. Carte des sols des Antilles (Guadeloupe—Martinique). ORSTOM, Antilles.

Cook PG, *et al*. 1998. Water balance of a tropical woodland ecosystem, Northern Australia: a combination of micro-meteorological, soil

DOI: 10.1002/hyp

physical and groundwater chemical approaches. *Journal of Hydrology* **210**(1–4): 161–177.

Crawford NH, Linsley RK. 1966. *Digital Simulation in Hydrology: Stanford Watershed Model IV*. Department of Civil Engineering, Stanford University: Stanford, California.

Dagain J, Paterne M, Westercamp D. 1981. La mise en place du massif volcanique Madeleine-Soufrière, Basse-Terre de Guadeloupe, Antilles. *Comptes Rendus de l'Académie des Sciences (Paris)* **2**: 921–926.

Dahlgren RA, Saigusa M, Ugolini FC. 2004. The Nature, Properties and Management of Volcanic Soils. In *Advances in Agronomy*. Sparks D (ed). Academic Press/University of Delaware: Newark; 113–182.

Donigan A, Bicknell B, Imhoff JC. 1995. Hydrological simulation program—Fortran (HSPF). In *Computer Models of Watershed Hydrology*. Singh VPE (ed). Water Resources Publications: Colorado; 395–442.

Dorel M, Roger-Estrade J, Manichon H, Delvaux B. 2000. Porosity and soil water properties of caribbean volcanic ash soils. *Soil Use and Management* **16**: 133–140.

Dubreuil PL. 1985. Review of field observations of runoff generation in the tropics. *Journal of Hydrology* **80**(3–4): 237–264.

Ecker A. 1976. Groundwater behaviour in Tenerife, volcanic island (Canary Islands, Spain). *Journal of Hydrology* **28**(1): 73–86.

Edijatno Nascimento NO, Yang X, Makhlouf Z, Michel C. 1999. GR3J: a daily watershed model with three free parameters. *Hydrological Sciences Journal* **44**(2): 263–278.

Elsenbeer H. 2001. Hydrologic flowpaths in tropical rainforest soilscapes—a review. *Hydrological Processes* **15**(10): 1751–1759.

Elsenbeer H, Vertessy RA. 2000. Stormflow generation and flowpath characteristics in an Amazonian rainforest catchment. *Hydrological Processes* **14**: 2367–2381.

Fontes JC, Pereira LS, Smith RE. 2004. Runoff and erosion in volcanic soils of Azores: simulation with OPUS. *CATENA* **56**(1–3): 199–212.

Fritsch J-M. 1992. *Les Effets du Défrichement de la Forêt Amazonienne et de la Mise en Culture sur l'Hydrologie de Petits Bassins Versants: opération ECEREX en Guyane française*. PhD thesis, Université des Sciences et Techniques du Languedoc, Montpellier.

Fujieda M, Kudoh T, de Cicco V, de Calvarcho JL. 1997. Hydrological processes at two subtropical forest catchments: the Serra do Mar, Sao Paulo, Brazil. *Journal of Hydrology* **196**(1–4): 26–46.

Godsey S, Elsenbeer H, Stallard R. 2004. Overland flow generation in two lithologically distinct rainforest catchments. *Journal of Hydrology* **295**(1–4): 276–290.

Hayami S. 1951. On the propagation of flood waves. *Disaster Prevention Research Institute Bulletin* **1**: 1–16.

Join J-L, Coudray J, Longworth K. 1997. Using principal components analysis and Na/Cl ratios to trace groundwater circulation in a volcanic island: the example of Reunion. *Journal of Hydrology* **190**(1–2): 1–18.

Kinner DA, Stallard RF. 2004. Identifying storm flow pathways in a rainforest catchment using hydrological and geochemical modelling. *Hydrological Processes* **18**: 2851–2875.

Lachassagne P. 2006. Chapitre: XIII DOM-TOM. 1. Martinique. In *Aquifères et Eaux souterraines en France*, ROUX JC (ed). AIH: Tome 2; 769–781.

Lesack LFW. 1993. Water balance and hydrologic characteristics of a rain forest catchment in the central Amazon Basin. *Water Resources Research* **29**(3): 759–773.

Malmer A. 1996. Hydrological effects and nutrient losses of forest plantation establishment on tropical rainforest land in Sabah, Malaysia. *Journal of Hydrology* **174**(1–2): 129–148.

Météo-France. 2005. Web site : http://www.meteofrance.com/.

Molicova H, Grimaldi M, Bonell M, Hubert P. 1997. Using TOPMODEL towards identifying and modelling the hydrological patterns within a headwater, humid, tropical catchment. *Hydrological Processes* **11**: 1169–1196.

Morell M, Jérémie JJ. 1994. La Guadeloupe au fil de l'eau, CCEE de Guadeloupe, ORSTOM, 121.

Moussa R, Bocquillon C. 1996. Algorithms for solving the diffusive wave flood routing equation. *Hydrological Processes* **10**(1): 105–123.

Nash JE, Sutcliffe JV. 1970. River flow forecasting through conceptual models part I: a discussion of principles. *Journal of Hydrology* **10**(3): 282–290.

Perrin C, Michel C, Andreassian V. 2001. Does a large number of parameters enhance model performance? Comparative assessment of common catchment model structures on 429 catchments. *Journal of Hydrology* **242**(3–4): 275–301.

Perrin C, Michel C, Andreassian V. 2003. Improvement of a parsimonious model for streamflow simulation. *Journal of Hydrology* **279**(1–4): 275–289.

Poulenard J, Podwojewski P, Janeau J-L, Collinet J. 2001. Runoff and soil erosion under rainfall simulation of Andisols from the Ecuadorian Paramo: effect of tillage and burning. *Catena* **45**: 185–207.

Quinn P, Beven K, Chevallier P, Planchon O. 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes* **5**: 59–79.

Rawlins BG, *et al*. 1998. Review of agricultural pollution in the Caribbean with particular emphasis on small island developing states. *Marine Pollution Bulletin* **36**: 658–668.

Roche M. 1963. *In Hydrologie de surface*. Gauthier-Villars Editeur: Paris.

Schellekens J, *et al*. 2004. Stormflow generation in a small rainforest catchment in the Luquillo Experimental Forest, Puerto Rico. *Hydrological Processes* **18**: 505–530.

Scholl MA, Ingebritsen SE, Janik CJ, Kauahikaua JP. 1998. Use of precipitation and groundwater isotopes to interpret regional hydrology on a tropical volcanic island; Kilauea volcano area, Hawaii. *Water Resources Journal* **196**: 48–63.

Singh VP. 1995. *Computer Models of Watershed Hydrology*. Water Resources Publications: Colorado.

Tixier P, Malezieux E, Dorel M. 2004. SIMBA-POP: a cohort population model for long-term simulation of banana crop harvest. *Ecological Modelling* **180**(2–3): 407–417.

Van Dijk AIJM, Bruijnzeel LA. 2004. Runoff and soil loss from bench terraces. 1. An event-based model of rainfall infiltration and surface runoff. *European Journal of Soil Science* **55**(2): 299–316.

Van Vosselen A, Verplancke H, Van Ranst E. 2005. Assessing water consumption of banana: traditional versus modelling approach. *Agricultural Water Management* **74**(3): 201–218.

Vertessy RA, Elsenbeer H. 1999. Distributed modeling of storm flow generation in an Amazonian rain forest catchment: effects of model parameterization. *Water Resources Research* **35**(7): 2173–2187.

Walsh RPD. 1980. Runoff processes and models in the humid tropics. *Zeitschrift fur Geomorphologie* **36**: 176–202.

WRB IWG. (Ed). 2006. World reference base for soil resources. *World Soil Resources*, No 103. FAO: Rome.

Ziegler AD, *et al*. 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. *Journal of Hydrology* **287**(1–4): 124–146.

Zimmermann B, Elsenbeer H, De Moraes JM. 2006. The influence of land-use changes on soil hydraulic properties: implications for runoff generation. *Forest Ecology and Management* **222**(1–3): 29–38.

5 Transport of a Nematicide in Surface and Ground Waters in a Tropical Volcanic Catchment.

Transport of a Nematicide in Surface and Groundwaters in a Tropical Volcanic Catchment

Jean-Baptiste Charlier* and Philippe Cattan CIRAD
Marc Voltz and Roger Moussa INRA

The aim of this article is to determine how the nematicide cadusafos [*S*,*S*-di-*sec*-butyl *O*-ethyl phosphorodithioate] contaminates water and soils at two scales, subcatchment and catchment. The study site was a small banana (*Musa* spp.)-growing catchment on the tropical volcanic island of Guadeloupe in the Caribbean. Two application campaigns were conducted, one in 2003 on 40% of the catchment and one in 2006 on 12%. The study involved monitoring for 100 d the surface water and groundwater flows and the cadusafos concentrations in the soil and in surface and groundwaters in a 2400 m^2 subcatchment and a 17.8 ha catchment. The results show that at the subcatchment scale the high retention in the A horizon of the soil limits the transport of cadusafos by runoff, whereas the lower retention of the molecule in the B horizon favors percolation toward the shallow groundwater. Comparing the losses of cadusafos at the subcatchment and at the catchment scales revealed that the nematicide re-infiltrated in the hydrographic network. Two successive phases of stream water contamination were observed, corresponding to two distinct contamination mechanisms: an event-dominated contamination phase (of <30 d) when transport was linked to overland flow during precipitation shortly after application, and a stabilized contamination phase when transport originated mainly from the drainage of the shallow aquifer. Lastly, comparing the losses of the two phases during 2003 and 2006 showed that shallow groundwater, which is promoted in such permeable soils under abundant tropical rainfalls, seems to be the main contributor to stream contamination.

Pollution from agricultural sources is an important issue in coastal areas and islands in tropical regions like Central America, the Caribbean, and Hawaii. In fact, pollution is often blamed for the degradation of coastal resources, such as fresh and marine water and flora and fauna (Kammerbauer and Moncada, 1998; Rawlins et al., 1998; McDonald et al., 1999; Li et al., 2001; Taylor et al., 2003; Castillo et al., 2006). Particularly in these tropical regions, banana plantations cause sanitary problems and severe diffuse pollution of water resources by pesticides (Henriques et al., 1997; Castillo et al., 2000; Beaugendre and Edmond-Mariette, 2005). Indeed, bananas are grown mostly in zones with high rainfall depth, which leads to washout and leaching of soil-applied pesticides. Moreover, many of the plantations in central America and the Caribbean islands are on Andosols (IUSS Working Group WRB, 2006) or volcanic soils with andic properties. Their large infiltration capacities enhance leaching (Poulenard et al., 2001; Cattan et al., 2007b). Besides, Andosols also present specific properties that influence pesticide retention on the soil matrix: that is, a high organic matter content and large cation and anion exchange capacity that varies according to pH (Wada and Okamura, 1980; Wada, 1989). In this context, it is difficult to predict the transport of soluble elements. Sansoulet et al. (2007), for example, showed that despite fast transport through soil horizons, fertilizer leaching was delayed. This hinders prediction of pesticide fate in such soils and their potential to reach surface waters. Paradoxically, little research has been conducted on soil and water contamination by pesticides in tropical catchments such as those in banana plantations. It then appeared necessary to improve our knowledge of pesticide transport processes in these conditions to help in assessing the associated environmental impact and find efficient means to limit pesticide transfer from the field to the catchment.

The aim of this paper was to identify, in a small tropical catchment with volcanic soils and mainly cultivated with bananas, the pathways and time course of the surface and groundwater contamination by a nematicide, cadusafos, used in banana plantations. The catchment is on the island of Guadeloupe in the French West Indies. The concentrations of cadusafos were monitored in soil and in surface and groundwaters at the scales of a 17.8 ha catchment and a 2400 m^2 subcatchment during two monitoring campaigns of 100 d, each starting after pesticide application. The two campaigns differed by the size of the area where the nematicide was applied: in the first the nematicide was applied over all the banana fields whereas in the second it was ap-

Published in J. Environ. Qual. 38:1031–1041 (2009).
doi:10.2134/jeq2008.0355
Freely available online through the author-supported open access option.
Received 7 Aug. 2008.
*Corresponding author (jb.charlier@gmail.com).
© ASA, CSSA, SSSA
677 S. Segoe Rd., Madison, WI 53711 USA

J.-B. Charlier and P. Cattan, CIRAD, UPR Systèmes Bananes et Ananas, Capesterre-Belle-Eau, Guadeloupe, F-97130 France; J.-B. Charlier, current address, Université de Franche-Comté-CNRS/UMR 6249 Chrono-environnement, UFR des Sciences et Techniques, 16 route de Gray, F-25030 Besançon cedex, France; M. Voltz and R. Moussa, INRA, Laboratoire d'étude des Interactions Sol-Agrosystème-Hydrosystème (LISAH), UMR AgroM-INRA-IRD, Bat. 24, 2 place Viala, 34060 Montpellier cedex 1, France.

plied only in the upper part of the catchment. This enabled us to analyze the effect of varying contributing areas on the contamination dynamics of catchment runoff.

Materials and Methods

Study Site

The area studied is the Féfé catchment (Fig. 1). It is on the volcanic Caribbean island of Basse-Terre in Guadeloupe (16°03′50′′ N, 61°37′12′′ W) (Fig. 1a,b), and covers 17.8 ha. It is a mountainous catchment at 318 to 428 m ASL that is divided along its length into two geomorphologically opposed zones (Fig. 1c). The northern half consists of a steep south-facing slope with gradients from 26 to 60%. The southern half consists of a short plateau with an average gradient of 9%, where the stream is perennial. In Guadeloupe, the climate is humid tropical with a maritime influence. There are two seasons: dry in February-March and rainy from July to November. The average annual rainfall in Féfé is 4200 mm. The catchment contains five banana farms. Fifty five percent of the catchment area is used for cultivating bananas, 40% is fallow with patches of flowers and grassland, and 5% consists of the man-made network of roads, platforms, and barns.

According to Charlier (2007), the geological context of Féfé is a system of cut-and-fill paleovalleys (Fig. 1c). Lava flows and pyroclastic deposits (nuées ardentes) filled two valleys that run northwest and southeast on a weathered substratum. The catchment is covered by a 4- to 8-m thick formation of lapilli and ash. Thus, the formations of nuées ardentes and lava flows shelter a deep aquifer on which the lapilli deposits shelter a shallow aquifer. Hydrogeological studies have shown that the main stream of the catchment drained the shallow aquifer as well as the deep aquifer downstream from the catchment (Charlier, 2007). As a result, groundwater flow is the main contributor to annual runoff at the catchment scale, and percolation from the shallow aquifer partly recharges the deep aquifer (Charlier et al., 2008). In periods of flooding, runoff on the slopes is mainly Hortonian: the runoff coefficient may reach 35% during a runoff event in a banana field on Andosol (Cattan et al., 2006) and it is enhanced on impermeable surfaces, such as roads, platforms, and barns. Soils over the catchment are classified as Umbric Andosol (IUSS WORKING GROUP WRB, 2006), which Dorel et al. (2000) studied in detail. The saturated hydraulic conductivities in the A (hA) and B horizons (hB) are 30 and 40 mm h^{-1}, respectively (Charlier et al., 2008).

Presentation of the Two Monitoring Campaigns

Two monitoring campaigns of cadusafos concentrations in soil and water were conducted to study the spatial and temporal variations of the contamination mechanisms. The zones of application are shown in Fig. 2, and the quantities applied as well as the duration of the monitoring periods are given in Table 1. In the "2003" campaign, cadusafos was applied several times between 3 and 21 Oct. 2003 on a set of banana fields distributed over the whole catchment and covering 40% of the catchment's total surface area; hydrological and chemical monitoring lasted from 3 Oct. 2003 to 11 Jan. 2004. During the "2006" campaign, cadusafos was only applied once on 5 July 2006 in a part of the catchment located upstream and covering 12% of the catchment's total surface area; hydrological and chemical monitoring lasted from 5 July 2006 to 23 Sept. 2006.

Hydrological Measurements

Figure 1d shows the location of the devices. Rainfall intensities were measured at four sites using tipping bucket rain gauges (ARG100, Campbell Scientific, Shepshed, Leicestershire, UK), with a sensitivity of 0.2 mm of rain per tip. Measurements from each rain gauge were integrated over a 2-min time step. We did not observe any space dependence of the recorded precipitations upstream and downstream from the small Féfé catchment. Thus, the average catchment rainfall was estimated as the arithmetic mean of the rainfall values at the four gauges.

Runoff was measured at the subcatchment scale and at the catchment scale. The subcatchment of 2400 m^2 was on the northern slope of the catchment and was entirely planted with banana. The gauging station at the subcatchment outlet consisted of a composite weir with a 90° V-notch, 0 to 0.24 m high. Water levels were recorded in 2-min time steps using a manometric probe (Diver, Van Essen Instruments, Delft, the Netherlands). The gauging station at the catchment outlet consisted of a composite weir with (i) a 90° V-notch, 0 to 0.50 m high, (ii) overlaid by a 1.95 m wide, 0.50 to 1.025 m high, rectangular weir, and (iii) for exceptional flood events, the shape of the outlet section above 1.025 m was assumed to be trapezoidal for flow estimations. Water levels were recorded in 2-min time steps using a PDCR1830 depth and level sensor (Campbell Scientific, Shepshed, Leicestershire, UK).

Six shallow piezometers (P1, P4, P7, P8, P10, P12) at depths between 1.5 and 5 m in the lapilli formation and two deep piezometers (FB and FD) between 15 and 30 m in the nuée ardentes and lava formations were monitored manually on a weekly basis. They were located across two transects upstream and downstream from the catchment.

Characteristics of Cadusafos and Application Rate

As stated previously, the pesticide molecule studied was the nematicide cadusafos, which is used in the French West Indies to control banana pests, particularly the nematode *Radopholus similis*. Since the banana crop is perennial, the nematicide is applied several times a year. It is classified as very toxic and dangerous for the environment according to FOOTPRINT (2006). Studies on the dissipation of cadusafos in Andosol in the Caribbean soils gave values of 9 to 15 ± 1 d for the half-life (DT50) and values between 50 and 620 L $kg^{-1}$for the distribution organic-C sorption constant (Koc) (Zheng et al., 1994; Lazrak, 2006). Cadusafos was applied in granulated form (Rugby 10G, FMC Corp., Philadelphia, PA) at the base of banana plants; application rate was 6 kg ha^{-1}, which corresponds to standard practice for banana plantations.

Sampling

To study the cadusafos dispersion in soils and water after application, the concentrations were monitored in the A and B soil horizons, in runoff water at the subcatchment and the catchment scales, and in groundwater.

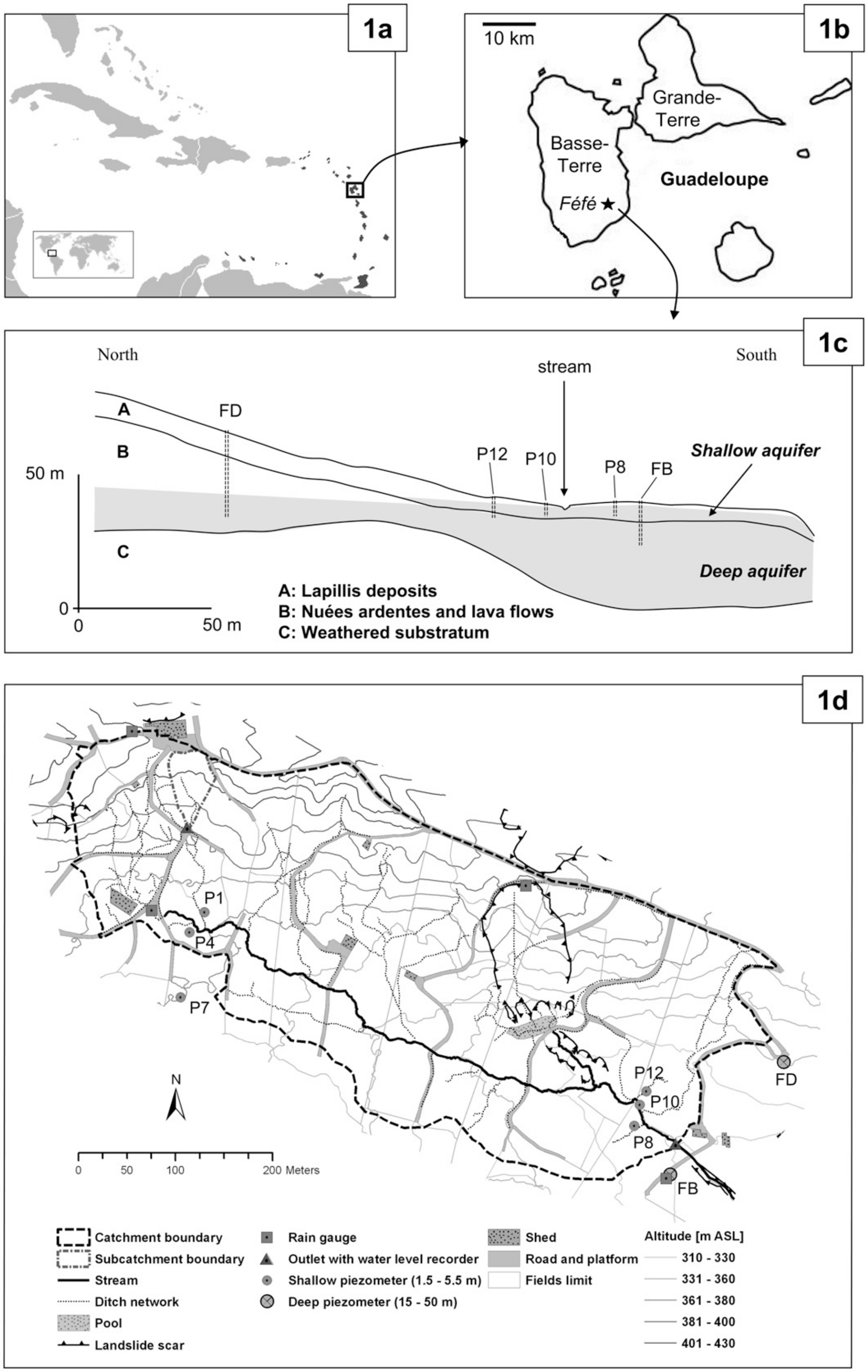

Fig. 1. Location of Guadeloupe in the Caribbean (1a) and location of Féfé on the island of Basse-Terre (1b); hydrogeological scheme of the Féfé catchment (1c) showing two overlapping aquifers; hydrological equipment in the Féfé catchment (1d).

Soil Sampling

The soil was sampled four times during each monitoring campaign, one time before application (24 Sept. 2003 and 27 June 2006) and three times after application (10, 53, and 94 d after the first application in 2003 and 5, 20, and 78 d after the single application in 2006). In 2003, the samples were taken

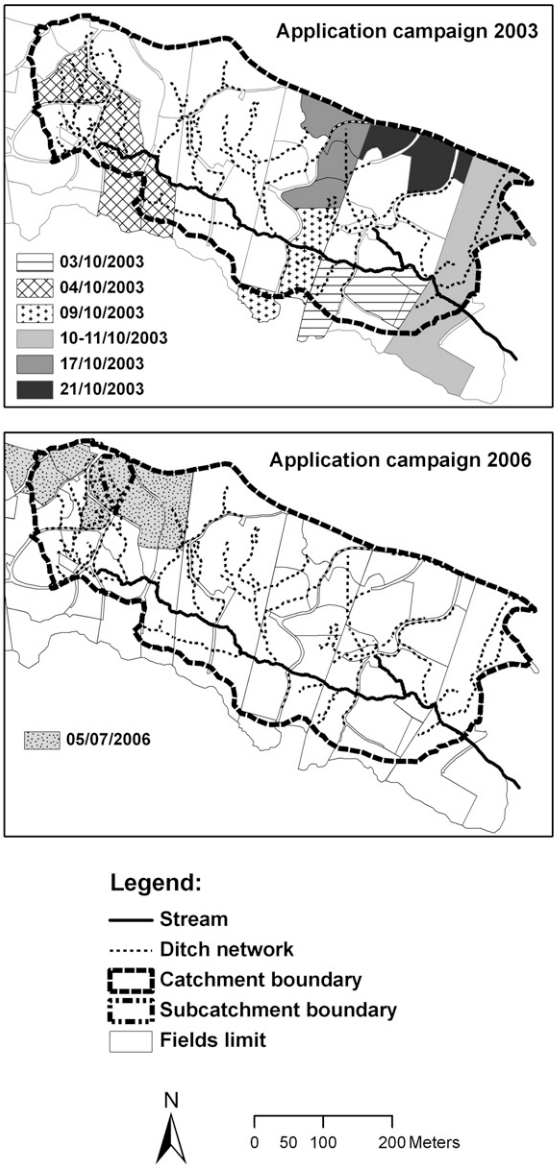

Fig. 2. Zones and dates of application of cadusafos for the campaigns in 2003 and 2006.

at each sampling time in nine fields distributed over the catchment so as to represent the upstream and downstream areas as well as the northern highland and the southern plateau. In 2006, the samples were taken only in four fields located in the area of pesticide application in the northern highland.

The soil was sampled using a hand auger. For each field, two bulked samples were taken at a depth of 0 to 20 cm in the A horizon (hA) and at a depth of 40 to 60 cm in the B horizon (hB). Each bulked sample was a mix of 20 samples spatially distributed in the field to account for the spatial heterogeneity of cadusafos application, which resulted from application of cadusafos at the base of each banana plant. Accordingly, 12 samples were taken between the rows, 4 between banana plants in the row, 2 at 30 cm upstream from the base of the banana plants, and 2 at 30 cm downstream. For each bulked sample, a fraction of about 500 g was taken, and then frozen at –18°C before analysis.

Table 1. Dates, surface areas treated, and hydrological monitoring for the campaigns in 2003 and 2006.

	Cadusafos application		Soil	Surface runoff at subcatchment outlet		Catchment runoff at catchment outlet		Groundwater in piezometers	
Date of application	Surface area treated	Amount applied	Soil sampling	Water sampling	Runoff measurements	Water sampling	Runoff measurements	Water sampling	Piezometric measurements
	m^2	kg							
				Campaign in 2003					
3 Oct. 2003	15,200	9.13	from 3 Oct. 2003 to 5 Jan. 2004, i.e., for 94 d	no	no	daily	from 3 Oct. 2003 to 11 Jan. 2004, i.e., for 100 d	weekly	from 3 Oct. 2003 to 11 Jan. 2004, i.e., for 100 d
4 Oct. 2003	10,700	6.43							
9 Oct. 2003	6,400	3.83							
10 and 11 Oct. 2003	17,000	10.22							
17 Oct. 2003	9,700	5.84							
21 Oct. 2003	8,000	4.78							
Total 2003	67,000	40.23							
				Campaign in 2006					
5 July 2006	19,400	11.64	from 5 July to 21 Sept. 2006, i.e., for 78 d	each flood event	from 1 July to 6 Sept. 2006 i.e., for 64 d	daily	from 1 July to 23 Sept. 2006, i.e., for 80 d	not done	not done

Water Sampling

Runoff at the Outlet of the Subcatchment (2006). Water was sampled at the outlet of the subcatchment, upstream from the weir, using an automatic sampler (sampler 900 MAX, American SIGMA, Loveland, CO) comprising 12 glass bottles previously rinsed with distilled water. The flow was intermittent at the subcatchment outlet and occurred only during flood events. Runoff water was sampled three times during each flood event at 2, 7, and 17 min after the water levels in the weir started to rise. This sampling frequency was chosen according to the observed rainfall-runoff time series at the subcatchment outlet to ensure that a sample was taken at each stage of rising, peak, and recession. The bottles were collected the day after each storm event. For each flood event, a bulked sample was then formed that consisted of the sum of the three samples of the event.

Runoff at the Outlet of the Catchment (2003 and 2006). In 2003, water was sampled at the Féfé catchment outlet with the same equipment as at the subcatchment outlet. However, the sampling strategy differed from that at the subcatchment scale because the catchment outlet flow was continuous. Each bottle of the sampler was filled with six subsamples of 100 mL taken at regular 4-h intervals, which formed an integrated sample for a day. The bottles were collected from the site every 2 or 3 d. From 27 Sept. 2003 to 7 Dec. 2003, each daily sample was selected for analysis. From 8 Dec. 2003 until 11 Jan. 2004, a bulked sample of 3 d was analyzed to restrict analytical costs. Inadequate functioning led to the loss of data between 14 and 30 Nov. 2003, 19 and 22 Dec. 2003, and 5 and 6 Jan. 2004. A sample of runoff water before application was also made up from a set of samples taken during 7 d (19–25 Sept. 2003).

In 2006, water was sampled using an automatic sampler (Simplex Mini, ORI Abwassertechnik, Hille, Germany), comprising one glass bottle. The water sample was collected from the site each day. As in 2003, each daily sample consisted of six subsamples of 100 mL taken every 4 h. From 6 July 2006 to 21 Aug. 2006, each daily sample was analyzed. Then, to restrict the number of analyses, from 22 Aug. to 8 Sept. 2006, we used bulked samples of 2 d and, from 9 to 18 Sept. 2006, bulked samples of 3 d. The sample taken before application was an average of the daily samples taken over 7 d (23–29 June 2006).

Groundwater (2003 and 2006). Groundwater was sampled using peristaltic pumps: a manual pump for shallow piezometers and an electric pump for deep piezometers. Before sampling, to prevent contamination between each piezometer, the material (plastic pipe) was systematically rinsed with distilled water and then with sampled groundwater. First, wells were purged of at least three well volumes with continuous pumping, and then they were sampled when groundwater regime was stabilized. In 2003, samples were taken every week from 10 Oct. to 20 Nov. 2003. Then, from 20 Nov. 2003 to 9 Jan. 2004, samples were taken twice a month. Sampling before application was conducted on 26 Sept. 2003. In 2006, we were unable to sample groundwater because piezometric levels were constantly deeper than the bottom of the piezometer in the upstream part of the catchment where cadusafos was applied.

Analytical Methods

The soil and water samples were stored frozen at −18°C before being sent for analysis at the Laboratory of Soil Analyses (INRA) in Arras, France. The soil samples were defrosted at 4°C before analysis. The gravimetric moisture content of the soil samples was measured on a subsample of 30 g of moist soil. Moisture content was taken into account to calculate the cadusafos content in the soil. Pure acetone was used for extraction with an Accelerated Solvent Extraction (ASE200 Dionex, Dionex Corp., Sunnyvale, CA) on a subsample of 20 g of moist homogenized soil. The liquid-liquid extraction was conducted using pure hexane. Then, pure hexadecane was added before partial rotative evaporation, followed by total evaporation under a light N flow. The dry residue was collected in 2 mL of hexane. Cadusafos was analyzed by capillary gas chromatograph (GC) using a Varian 3400 (Varian, Inc. Corporate Headquarters, Palo Alto, CA) equipped with a split/splitless injector, a thermo-ionic detector (TSD), and a Restek column RTX 200 (15 m; 0.53 mm; 1 μm). Helium was used as the gas vector at a flow rate of 2 mL min^{-1}. The temperature of the detector was 290°C, that of the injector was 260°C, and that of the stove gradient was 150 to 250°C.

The water samples were defrosted at +4°C before analysis. Cadusafos was extracted from the water by the automaton Autotrace Zymark (Zymark Corp., Hopkinton, MA) for solid phase extraction. An aqueous sample of 200 mL was homogenized: small volumes of organic solvent were added to elute the sample, followed by hexadecane. The sample was placed in a rotative evaporator for partial evaporation and then under a light N flow for total evaporation. The residue was diluted in 2 mL of hexane. Lastly, the analysis of cadusafos was conducted using GC with the same material and under the same chromatographic conditions as for the soil.

The detection limits of cadusafos contents in soil and water were 0.5 μg kg^{-1} and 0.01 μg L^{-1}, respectively. A value of zero was attributed to amounts below these detection limits. In principle, this can lead to a significant bias with regard to the calculation of quantities when many samples have concentrations below this level. However, this was not the case in our study.

Estimating the Amount of Pesticide Applied and Pesticide Losses

The amount of cadusafos applied in the catchment was calculated on the basis of the recommended Rugby application rate in a field (6 kg ha^{-1} of active ingredient) and of the areas treated. The amount applied and the fields treated were controlled on the field during application days. Pesticide losses by runoff water were computed on a daily basis from the measured discharges and cadusafos concentrations. When only average concentrations over 2 or 3 d were known, the daily losses were estimated as a pro rata of the total quantity transported over the 2 or 3 d weighted by the observed daily runoff volume.

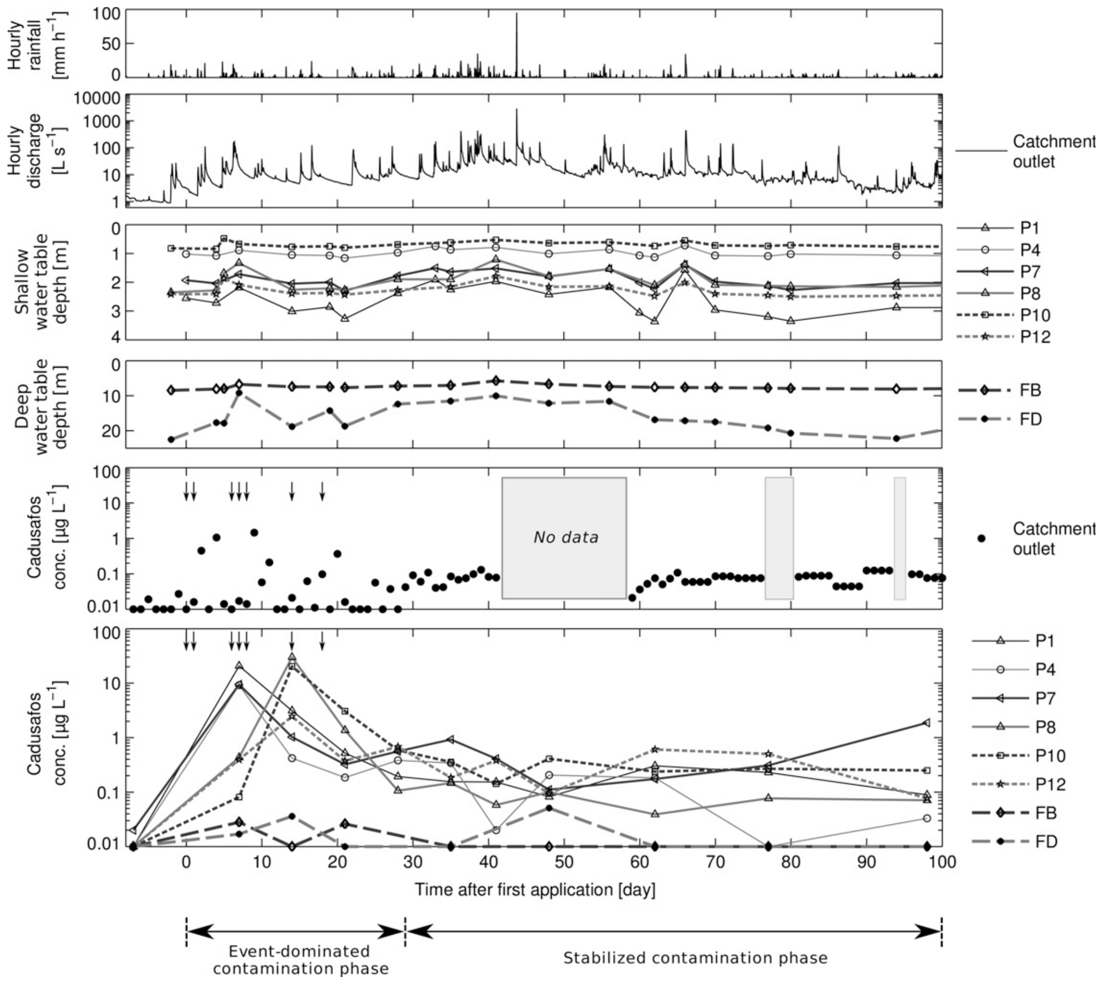

Fig. 3. Campaign in 2003 (application dates [showed by arrow] between 3 and 21 Oct. 2003): time series of rainfall, discharge at the catchment outlet, groundwater depths, and cadusafos concentrations.

Results

Hydrological Characteristics of the Two Monitoring Campaigns

The two monitoring campaigns occurred during two periods with contrasted hydrological conditions. Rainfall depth, discharge, and groundwater levels are plotted in Fig. 3 and 4, and hydrological characteristics are in Table 2.

- The 2003 campaign (Fig. 3) was conducted from 3 Oct. 2003 to 11 Jan. 2004, that is, 100 d of monitoring during the cyclonic season. The period was characterized by abundant rainfalls (total of 2185 mm) and generally by high rainfall intensities with an observed hourly maximum of 94.5 mm h^{-1}. Daily rainfall exceeded 25 mm in one-third of the monitored days. This period corresponds to a period of high water levels, with the average daily discharge ranging from 2 to 125 L s^{-1} and a global runoff coefficient of 42.5% at the catchment scale. Fluctuations of the shallow groundwater (piezometers P1 to P12) were <1.9 m at depths varying initially between 0.6 and 3.4 m depending on the sites. Fluctuations of the deep groundwater at piezometers FD and FB were 2.7 and 13.4 m at depths of 22.6 and 5.8 m, respectively.
- The 2006 campaign (Fig. 4) took place from 5 July to 23 Sept. 2006 at the start of the cyclonic season, that is, 80 d. The period was characterized by moderate rainfalls (611 mm). The medium rainfall intensities were lower than during the 2003 campaign: the hourly maximum rainfall intensity was 15.6 mm h^{-1}. Daily rainfalls exceeded 25 mm only on 5 d of the 80. This corresponds to a period of low water levels, with daily discharge ranging from 0.1 to 20 L s^{-1} and a global runoff coefficient of 22.2% at the catchment scale.

These observations are in accordance with those of Charlier et al. (2008) who studied the main hydrological processes in the Féfé catchment in 2003 and 2004. Hence, using the same method of hydrograph separation between surface runoff and baseflow, the comparison of the 2003 and 2006 discharge series at the catchment scale confirmed that (i) the wetter the initial conditions, the larger the surface runoff coefficient and (ii) groundwater flow is the main contributor to catchment runoff whatever the year since it amounted to two-thirds of runoff although runoff volume was sevenfold higher in 2003 than in 2006.

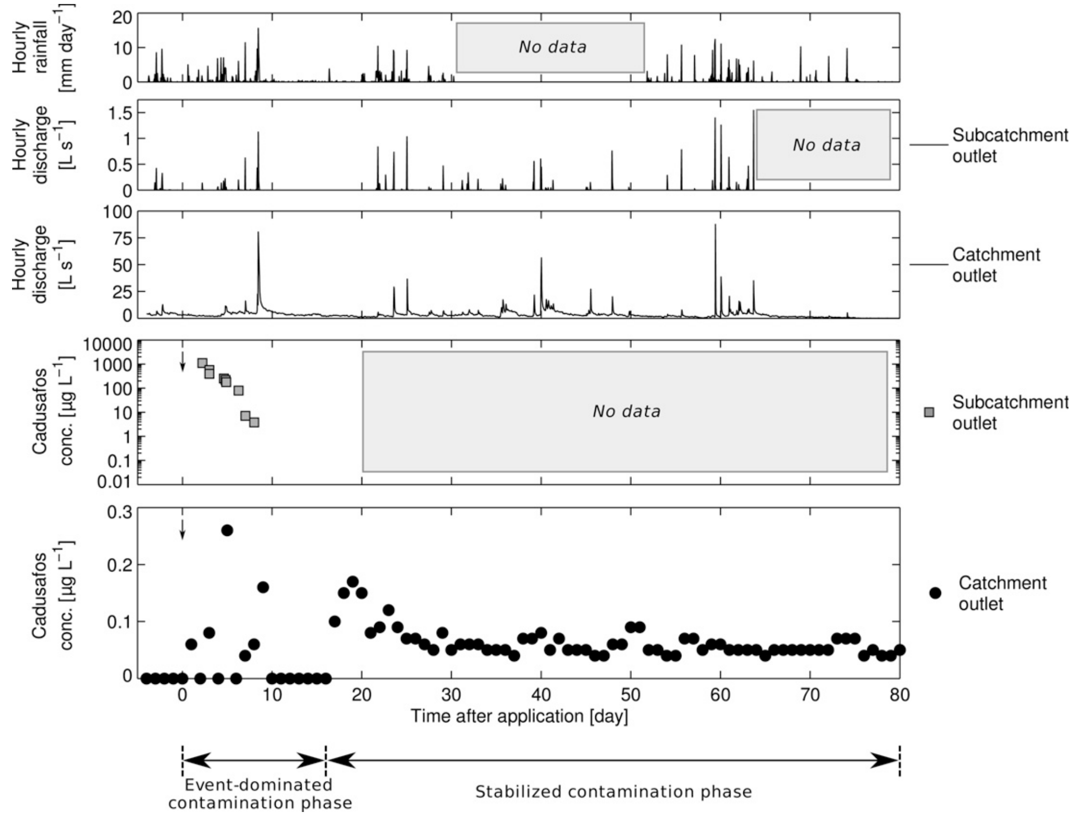

Fig. 4. Campaign in 2006 (date of application [showed by arrow] 5 July 2006): time series of rainfall, discharges, and cadusafos concentrations at the subcatchment outlet and at the catchment outlet.

Table 2. Hydrological characteristics of the time series during the application campaigns in 2003 and 2006.

Hydrological characteristics	Campaign in 2003 (100 d)	Campaign in 2006 (80 d)
Rainfall		
Rainfall depth, mm	2185	611
Maximum hourly rainfall intensity, mm h^{-1}	94.5	15.6
Surface runoff at the subcatchment scale		
Surface runoff coefficient, % of rainfall	-	5.7
Variation interval of surface runoff coefficient, % of rainfall, at the flood event scale	-	0–21
Variation interval of average daily discharge, L s^{-1}	-	0–0.25
Groundwater		
Variation interval of shallow groundwater depth, m	0.6–3.4	-
Variation interval of deep groundwater depth, m	2.7– 22.6	-
Runoff at the catchment scale		
Runoff coefficient, % of rainfall	42.5	22.2
Surface runoff coefficient†, % of rainfall	15.7	8.6
Baseflow coefficient†, % of rainfall	26.8	13.6
Variation interval of surface runoff coefficient, % of rainfall, at the flood event scale	1–38	0–14
Variation interval of average daily discharge, L s^{-1}	2–125	0.1–20

† Denotes that hydrograph separation was performed using the straight line method described by Charlier et al. (2008).

Persistence of Cadusafos in the Andosol

Table 3 shows the evolution in cadusafos concentrations for the upper soil horizon hA and the deeper horizon hB of the treated fields during the 2003 and 2006 campaigns. The initial cadusafos concentrations in the soil before application were small and similar for all fields sampled in 2003 and 2006, ranging between 8.4 and 11.3 µg kg^{-1} for hA, and between 1.1 and 4.4 µg kg^{-1} for hB. These concentrations before application indicate that cadusafos is persistent in the soil since the previous applications dated more than 3 mo. The new applications at the start of the monitoring periods caused a significant increase in soil concentrations: 5 to 10 d after application, the observed maxima of average field concentrations were 80 (± 124) and 38 (± 23) µg kg^{-1} for hA, and 28 (± 30) and 13 (± 14) µg kg^{-1} for hB in 2003 and 2006, respectively. The observed peaks were simultaneous for the two horizons, which suggests that the molecule migrated rapidly in depth.

Table 3 also shows that there was a large spatial variation of cadusafos concentrations in each horizon among the set of sampled

Table 3. Average cadusafos concentrations in soils for the A horizon (hA) and the B horizon (hB) of the treated fields.

Time after application	Average concentration of cadusafos in hA	Average concentration of cadusafos in hB	Probability level of difference between hA and hB
d	———μg kg⁻¹———		
Campaign in 2003			
−9	8.4 (5.8)†	1.1 (2.1)	***
10	80.0 (123.8)	28.5 (30.4)	ns‡
53	18.2 (14.6)	7.5 (7.8)	**
94	18.6 (7.2)	4.0 (2.8)	***
Campaign in 2006			
−8	11.3 (7.3)	4.4 (6.2)	ns
5	37.8 (23.4)	13.5 (14.1)	*
20	16.9 (9.6)	9.4 (7.2)	ns
75	10.8 (6.5)	0.9 (0.4)	*

* Indicates whether the difference in average cadusafos concentrations between hA and hB are statistically different at the 0.05 probability level.

** Indicates whether the difference in average cadusafos concentrations between hA and hB are statistically different at the 0.01 probability level.

*** Indicates whether the difference in average cadusafos concentrations between hA and hB are statistically different at the 0.001 probability level.

† Standard deviation of observed concentrations is indicated in parentheses.

‡ ns = not significant.

fields and that statistically significant differences in soil concentration between hA and hB were detected for three sampling dates among four in 2003 and for two sampling dates among four in 2006. As expected, concentrations in the upper horizon hA on which cadusafos was applied were larger than in hB, which was contaminated by compounds leaching from hA. Besides, soil concentrations did not differ statistically between the abundant rainfall period in 2003 and the moderate rainfall period in 2006. This could be explained by the fact that in both years no drought occurred and consequently soil moisture content always remained close to saturation, which ensured similar degradation rates.

Transport Processes

Surface Runoff

Cadusafos transport by surface runoff could be analyzed using water concentration data from the subcatchment outlet in 2006 (Fig. 4), since at this scale there was no contribution of groundwater to runoff. First, note that the total losses of cadusafos by runoff at the subcatchment outlet during 20 d represented 6.4 g ha^{-1}, that is, 0.1% of the total mount applied in 2006. The maximum concentration in runoff water was 1100 μg L^{-1} and was observed during the first flood event after application. Then concentrations fell rapidly during the next flood events to 3.7 μg L^{-1} (Fig. 4). Figure 5 represents the cumulative losses of cadusafos and the cumulative volume of surface runoff at the subcatchment scale as a function of time. We observed that 90% of cadusafos losses during the monitoring period occurred the first 6 d after application, which cumulated 3.6 m^3 of surface runoff (i.e., 1.5 mm depth) under 63 mm of rainfall. Between 6 and 9 d after application, the last 10% of cumulative cadusafos losses occurred despite an increase in cumulative surface runoff volume from 3.6 to 13.4 m^3 d^{-1} under 86.2 mm of rainfall. This pattern indicated that the amount of active ingredient available to runoff water decreased rapidly after application.

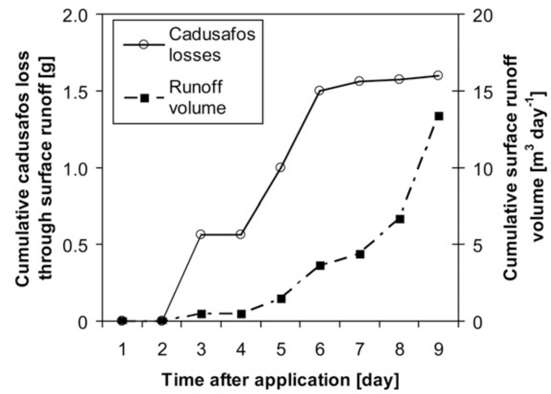

Fig. 5. Cumulative cadusafos losses and cumulative surface runoff volume after application at the subcatchment scale (Campaign in 2006).

Groundwater

Local contamination of the shallow groundwater was monitored in 2003 by piezometers P1 to P12 (Fig. 3), situated in fields where cadusafos was applied. The contamination pattern was similar for all piezometers. First, before application, cadusafos concentrations in all piezometers were below the detection limit (0.01 μg L^{-1}), except for P7, where a low concentration of 0.02 μg L^{-1} was found. This suggests that the persistence of the molecule in shallow groundwater is limited and does not exceed the delay between two applications. Second, after application, groundwater concentrations increased significantly for the first sampling dates, 6 to 7 d after application, with a mean concentration peak of 15.34 (± 10.02) μg L^{-1}. Then, 2 wk after this peak, the concentration dropped to reach a concentration plateau of an average of 0.29 μg L^{-1} and varying between 0.01 and 1.88 μg L^{-1}.

Regarding deep groundwater, in Fig. 3, initial concentrations before application in the deep piezometers FB and FD were below the detection limit, as for the shallow groundwater. After application, two concentration peaks very close to the detection limit were observed (maximum value of 0.05 μg L^{-1}). In both piezometers, however, the molecule became undetectable 6 wk after application.

Catchment Runoff

Identification of Two Phases of Water Contamination after Application. During each of the two monitoring periods, 2003 and 2006, two successive phases of water contamination by cadusafos could be distinguished at the catchment outlet (Fig. 3 and 4). The first phase started after the first application and exhibited an erratic variation of water contamination, with maximum daily mean concentrations corresponding to the storm events. This phase lasted about 28 d in 2003 and 16 d in 2006 and exhibited maximum daily mean contamination peaks of 1.5 μg L^{-1} in 2003 and 0.26 μg L^{-1} in 2006. We named it the “event-dominated contamination phase.” During the event-dominated phase in 2006, the concentration peaks at the catchment outlet mostly corresponded to surface runoff events at the subcatchment outlet (Fig. 4). This can be explained by the large concentrations of cadusafos in overland flow that occurred during 10 d after application in 2006 (Fig. 4). Moreover, as can be seen on Fig. 3 and 4, during 2 wk after application, catchment runoff exhibited episodic nil concentrations of cadusafos. Between 10 and 16 d after application in 2006 (Fig. 4), when no precipitation occurred, these nil concentrations corresponded to periods during which catchment runoff came from groundwater only.

The first phase was followed by a "stabilized contamination phase" exhibiting smaller fluctuations around an average contamination level of about 0.07 μg L^{-1} in 2003 and 0.06 μg L^{-1} in 2006. This second phase started 29 and 17 d after the first application in the 2003 and 2006 campaigns, respectively. The cadusafos concentrations in runoff water at the catchment outlet varied little although the relative contribution of groundwater and surface runoff to stream runoff varied largely with flood occurrence. In 2006, the two phases can be clearly distinguished: the stabilized phase started the 17th day after application, just after a few days without any flood event, and thus without overland flow at the subcatchment outlet.

The cadusafos losses at the catchment outlet 78 d after application corresponded to 0.03% of the total amount applied in 2003 and to 0.01% in 2006. Moreover, it must be stressed that the losses arose mainly during the stabilized phase, which delivered 65% of the total 2003 losses and 69% of the 2006 losses. This was expected because, even if pesticide concentration peaks remained higher in the event-dominated phase, the duration of the stabilized phase was larger. Nevertheless, these results should be nuanced by the fact that the sampling strategy at the catchment outlet (daily mean concentration constituted of six samples every 4 h) probably underestimated concentration peaks because the small flood events may last only a few hours.

Buffering Effect of the Contamination Level between Subcatchment and Catchment Scales. The maximum concentrations at the subcatchment outlet were almost 4000-fold higher than at the catchment outlet, which indicates the existence of dilution and/or buffering effects between the subcatchment and catchment scales. Even if this buffering effect should be nuanced by the probably slightly underestimated concentration peaks at the catchment scale (due to the sampling strategy detailed above), we have considered that this effect was partly responsible for the concentration decrease from upstream to downstream. To test this buffering hypothesis, we compared the cumulative loads of cadusafos supposed to be transported in 2006 via the overland flow downstream from the treated fields and the loads observed in runoff at the catchment outlet. The loads of cadusafos transported from the treated fields were estimated by assuming that the loads, expressed per surface area from the subcatchment of 2400 m^2, were similar for all the treated fields of the catchment (19,400 m^2). Results show that 8 d after application, the cumulative load of cadusafos from the treated fields was 60-fold larger than that at the catchment outlet (cumulative loads of 12.4 and 0.2 g, respectively). This pattern suggests that cadusafos infiltrated in the ditch and hydrographic networks at a very high rate before reaching the catchment outlet. Along with the dilution effect by surface runoff on nontreated fields (fallow and grassland) and by noncontaminated groundwater, these results point out that the buffering effect due to cadusafos seepage in the ditches is likely to be an important process explaining the changes in contamination level between the field and catchment scales.

Discussion

This study attempted to determine the mechanisms of contamination of water and soil compartments by a nematicide, cadusafos, in a cultivated catchment of a volcanic tropical region. Our observations at the subcatchment scale show that surface runoff must be considered as a main pathway for water contamination by cadusafos. This phenomenon has been widely observed at this scale for different types of pesticides in different climates (Leonard, 1990; Lennartz et al., 1997; Donald et al., 1998; Louchart et al., 2001; Leu et al., 2004). As already reported, most pesticide losses via this process occurred during the first rainfall events following the application. However, in our case, the total losses of pesticide by surface runoff were small, representing <0.1% of the total amount applied on the field, which is much lower than the losses usually observed at the same scale (Leonard, 1990; Gentry et al., 2000; David et al., 2003). These results are consistent with those obtained by Saison et al. (2008) on an experimental field in the same pedoclimatic context. Those authors explained the low losses by a rapid depletion of cadusafos in the very first centimeters of the soil, due to both a rapid degradation of cadusafos after application and its migration downward once the applied cadusafos granules had dissolved, which took a week. This situation differs from other study site where most soil-applied pesticides remain in the surface soil layer for several months; this is notably the case where the methods of pesticide application (spraying for instance) and soil conditions are different (e.g., Leonard, 1990; Louchart et al., 2001).

In parallel, our results also show that the contamination by cadusafos affected mainly the shallow aquifer, which is a consequence of the high infiltrability of the Andosols. The concentration peaks of the shallow groundwater (reaching 15 μg L^{-1}) and the shallow piezometric levels suggest the existence of relatively homogeneous and rapid percolation processes within the soil, which cause the contamination of the shallow aquifer in less than a week. Later, these percolations favor the dilution of the contamination by the transfer of less polluted water (at a concentration level of 0.29 μg L^{-1}). These results are coherent with the high percolation rates in the deep soil horizons (40 mm h^{-1}) and the absence of vertical hydraulic discontinuity in the shallow aquifer (Charlier et al., 2008). In contrast, the very low concentration found in the deep piezometers reveals the separation that exists between a shallow aquifer exposed to high and rapid contamination and a deep aquifer that is barely affected or not at all by pesticide percolation (piezometers FD and FB in lava flows and nuées ardentes). This separation is generally linked to the geological structure of the site (e.g., Fenelon and Moore, 1998). In the Féfé catchment, a weathered ash layer over 1 m thick with low porosity at the base of the lapilli formation likely filtered the percolating pesticides.

The analysis of cadusafos concentration variations at the catchment outlet showed large and constant contamination of runoff water during 100 d after application. The observed daily mean concentrations of cadusafos, ranging from maximum values of 1.5 μg L^{-1} in 2003 and 0.26 μg L^{-1} in 2006 during the first rainfall events after application to 0.09 and 0.06 μg L^{-1} after 80 d, were well within the range of those measured by Castillo et al. (2006) in the water of a ditch draining 12 ha of a banana plantation in Costa

Rica, namely from 0.17 to 0.48 μg L^{-1} for a week after application and above 0.02 μg L^{-1} a month afterward. On a larger scale, in the Suerte basin in Costa Rica (38 200 ha with 15% planted with banana), the concentrations of cadusafos in surface water were also similar, that is, between 0.10 and 1.00 μg L^{-1} depending on the sampling site (Castillo et al., 2000). It therefore seems that the phenomenon of water contamination by cadusafos applied in banana plantations is not site-specific.

This study also provides insights into events that are likely to happen in catchment runoff contamination. In particular, the observation of two phases in the contamination dynamics of catchment runoff water highlights the different contributions of surface runoff and groundwater flow to catchment pollution. The contamination of surface runoff just after application was fast with large concentration peaks but decreased strongly (1000-fold) in <10 d whereas the contamination of the groundwater increased more slowly from hillslopes to the stream (between 16 and 28 d). That change from the first to the second phase may be related to the time transfer of the contaminated groundwater below the treated field to the outlet of the catchment. Consequently, in a first phase lasting 16 to 28 d after first application, erratic variation of water contamination of catchment runoff (concentration peaks reaching 1.5 μg L^{-1}) closely followed the flood events when surface runoff occurred. Indeed, during a week after application in 2006, large concentrations in overland flow ranging from 1100 to 3.7 μg L^{-1} were observed downstream from the treated fields. After that phase, catchment runoff concentrations stabilized near 0.1 μg L^{-1} due to the convergence of pesticide levels in surface and groundwater flows. A likely explanation of this result is that the concentration levels of the groundwater and the surface runoff were similar during this second phase, which can be confirmed in part by our observations. In fact, 8 d after the first application, the contamination of surface runoff at the subcatchment outlet had already largely decreased to a few micrograms per liter. If we refer to the concentrations measured in surface runoff in similar conditions (Saison et al., 2008), they declined to 0.2 μg L^{-1} 20 d after application. If we also account for possible dilution effects due to surface runoff from the nontreated fields and noncontaminated groundwater, it is therefore likely that surface runoff water contributing to catchment runoff was contaminated at nearly the same level as groundwater, namely 0.3 μg L^{-1}.

Although the contamination dynamics changed between the two phases, the average concentration level in stream runoff remained similar between the two phases for each monitoring period: 0.14 and 0.05 μg L^{-1} in the first phase and 0.07 and 0.06 μg L^{-1} in the second phase for 2003 and 2006, respectively. In fact, the highest surface runoff concentrations in the first phase were compensated by the low base flow concentrations whereas in the second phase the decrease in the surface runoff water contamination was compensated by an increased and more continuous contribution of the groundwater contamination. This finding differs markedly from the contamination dynamics observed in many other environments (e.g., Thurman et al., 1991; Ng et al., 1995; Louchart et al., 2001) where, at the catchment scale, large changes in concentration levels with time were observed even several weeks after the pesticide application. Finally, despite the similar range of cadusafos concentrations in stream runoff between the two monitoring periods, the total loads in 2003 were higher than in 2006: losses of 0.03 and 0.01% of total amount applied, and maximum concentration peaks at 1.5 and 0.26 μg L^{-1}, respectively. This change of loads was consistent with the higher hydrological flows in 2003 than in 2006 and the different amount applied, 40.2 kg in 2003 and 11.6 kg in 2006. However, even if pesticide loads were lower during the event-dominated contamination phase, pesticide concentrations remained higher in this phase, which may have a different biological impact on the stream.

To verify the main hypothesis about the pesticide transport processes highlighted above, a modeling approach should be developed to quantify the spatial and temporal variability of pesticide losses in soil, and surface and groundwaters. Implementing such a runoff pesticide model in a cultivated context of permeable and saturated soils under abundant rainfalls will require taking into account some specific processes. Hence, to simulate water flows and pesticide transport, a runoff pesticide modeling strategy should include the following elements: (i) the rainfall redistribution by banana plant (Cattan et al., 2007a) that influenced runoff at the plot scale (Charlier, 2007) and the fate of fertilizers (Sansoulet et al., 2007) and nematicide (Saison et al., 2008) and (ii) the surface/groundwater exchanges to simulate the re-infiltration of overland flow in ditches on hillslopes as well as the aquifer drainage by the stream. The development of such a runoff pesticide model calls for further studies to better understand the degradation and the mobilization processes of the nematicide in soil horizons.

Conclusions

The aim of this study was to identify the mechanisms of contamination of soil and water compartments at the both subcatchment and catchment scales by the nematicide cadusafos. The study highlights the environmental impact of pesticide application in cultivated areas in pedoclimatic conditions where rainfall is abundant, soils permeable, and organic matter content high.

The first important result is the distinction of two contamination phases, corresponding to the different contributions of surface and groundwater flows to runoff contamination at the catchment outlet. This pattern seems to be promoted in a context where high infiltration rates in fields and ditches lead to rapid pesticide lixiviation in deep horizons, and then in shallow groundwater by percolation. To manage water resources, this information should be considered to limit pesticide dispersion in groundwater as well as in streamflow.

A second result is that the contamination levels of surface water, as well as shallow and deep groundwaters, reflect the geological structure of the Féfé catchment: that is, a shallow aquifer in the most recent deposits that is rapidly exposed to pollution and a deeper aquifer that is relatively protected from the pollution coming from the treated fields. These results confirm the importance of knowing the geological structure and the major hydrological processes to better study the water contamination dynamics of basins on permeable substrates, for which the water balance exhibits the large contribution of groundwater flows to the stream contamination.

In some situations where water pollution is largely due to surface runoff on hillslopes, one of the solutions to limit pollution in streams is to encourage infiltration uphill, downstream from the fields, for example by implementing grassy strips (see for a review Lacas et al., 2005) or by favoring infiltration in the hydrographic network. Indeed in the case of Féfé catchment, it seems that re-infiltration of runoff in the hydrographic network buffered contamination peaks. But given the rapid propagation of percolation flow to groundwater and the large contribution of groundwater to catchment runoff, increasing the infiltration of contaminated surface water would principally aggravate the contamination of the shallow aquifer. It would somewhat lower the runoff concentration peaks at the catchment outlet without strongly limiting the total loads of pesticides in runoff water. Finally, the only conceivable way of reducing pollution is to reduce the treated areas and/or the rates of application in the fields.

Acknowledgments

We are grateful to Germain Onapin, Colbert Béhary, and Claire Eme for field and laboratory work. This work was carried out with the financial support of the Guadeloupe Region (FWI), the Ministère de l'Ecologie et du Développment Durable (France), the European Community under the project "Assessment of water-pollution risks associated with agriculture in the French West Indies: management at the catchment scale", and the ANR- Agence Nationale de la Recherche - The French National Research Agency under the Programme Agriculture et Développement Durable, project ANR-05-PADD-010, GeDuQuE. We thank the Laboratory of Soil Analyses in Arras for all chemical analyses of soil and water samples.

References

Beaugendre, J., and P. Edmond-Mariette. 2005. Rapport d'information sur l'utilisation du chlordécone et des autres pesticides dans l'agriculture martiniquaise et guadeloupéenne. no. 2430. Assemblée Nationale, Paris, France.

Castillo, L.E., E. Martinez, C. Ruepert, C. Savage, M. Gilek, M. Pinnock, and E. Solis. 2006. Water quality and macroinvertebrate community response following pesticide applications in a banana plantation, Limon, Costa Rica. Sci. Total Environ. 367:418–432.

Castillo, L.E., C. Ruepert, and E. Solis. 2000. Pesticide residues in the aquatic environment of banana plantation areas in the north Atlantic zone of Costa Rica. Environ. Toxicol. Chem. 19:1942–1950.

Cattan, P., F. Bussière, and A. Nouvellon. 2007a. Evidence of large rainfall partitioning patterns by banana and impact on surface runoff generation. Hydrol. Processes 21:2196–2205.

Cattan, P., Y.-M. Cabidoche, J.-G. Lacas, and M. Voltz. 2006. Effects of tillage and mulching on runoff under banana (*Musa* spp.) on a tropical Andosol. Soil Tillage Res. 86:38–51.

Cattan, P., M. Voltz, Y.-M. Cabidoche, J.-G. Lacas, and J. Sansoulet. 2007b. Spatial and temporal variations in percolation fluxes in a tropical Andosol influenced by banana cropping patterns. J. Hydrol. 335:157–169.

Charlier, J.-B. 2007. Fonctionnement et modélisation hydrologique d'un petit bassin versant cultivé en milieu volcanique tropical. Ph.D. diss. Université des Sciences et Techniques du Languedoc, Montpellier II.

Charlier, J.-B., P. Cattan, R. Moussa, and M. Voltz. 2008. Hydrological behaviour and modelling of a volcanic tropical cultivated catchment. Hydrol. Processes 22:4355–4370.

David, M.B., L.E. Gentry, K.M. Starks, and R.A. Cooke. 2003. Stream transport of herbicides and metabolites in a tile-drained, agricultural watershed. J. Environ. Qual. 32:1790–1801.

Donald, W.W., A.T. Hjelmfelt, and E.E. Alberts. 1998. Herbicide distribution and variability across Goodwater Creek watershed in north central Missouri. J. Environ. Qual. 27:999–1009.

Dorel, M., J. Roger-Estrade, H. Manichon, and B. Delvaux. 2000. Porosity and soil water properties of caribbean volcanic ash soils. Soil Use Manage. 16:133–140.

Fenelon, J.M., and R.C. Moore. 1998. Transport of agrichemicals to ground and surface water in a small central Indiana watershed. J. Environ. Qual. 27:887–894.

FOOTPRINT. 2006. The FOOTPRINT pesticide properties database. Database collated by the University of Hertfordshire as part of the EU-funded FOOTPRINT project (FP6-SSP-022704) Available at http://www.eu-footprint.org/ppdb.html (verified 4 Feb. 2009).

Gentry, L.E., M.B. David, K.M. Smith-Starks, and D.A. Kovacic. 2000. Nitrogen fertilizer and herbicide transport from tile drained fields. J. Environ. Qual. 29:232–240.

Henriques, W., R.D. Jeffers, T.E. Lacher, and R.J. Kendall. 1997. Agrochemical use on banana plantations in latin America: Perspectives on ecological risk. Environ. Toxicol. Chem. 16:91–99.

IUSS Working Group WRB (ed.) 2006. World reference base for soil resources 2006. World Soil Resources Rep.103. FAO, Rome.

Kammerbauer, J., and J. Moncada. 1998. Pesticide residue assessment in three selected agricultural production systems in the Choluteca River Basin of Honduras. Environ. Pollut. 103:171–181.

Lacas, J.-G., M. Voltz, V. Gouy, N. Carluer, and J.-J. Gril. 2005. Using grassed strips to limit pesticide transfer to surface water: A review. Agron. Sustain. Dev. 25:253–266.

Lazrak, E.G. 2006. Devenir du cadusafos sur des sols volcaniques de Guadeloupe sous culture bananière. Mémoire de DEA, Inst. Natl. Polytechnique de Lorraine, Vandoeuvre-Les-Nancy, France.

Lennartz, B., X. Louchart, P. Andrieux, and M. Voltz. 1997. Diuron and simazine losses to runoff water in Mediterranean vineyards. J. Environ. Qual. 26:1493–1502.

Leonard, R.A. 1990. Movement of pesticides into surface waters. p. 303–350. *In* H.H. Cheng (ed.) Pesticides in the soil environment: Processes, impacts and modelling. SSSA, Madison, WI.

Leu, C., H. Singer, C. Stamm, S.R. Müller, and R.P. Schwarzenbach. 2004. Simultaneous assessment of sources, processes and factors influencing herbicide losses to surface waters in a small agricultural catchment. Environ. Sci. Technol. 38:3827–3834.

Li, Q.X., E.C. Hwang, and F. Guo. 2001. Occurrence of herbicides and their degradates in Hawaii's groundwater. Bull. Environ. Contam. Toxicol. 66:653–659.

Louchart, X., M. Voltz, P. Andrieux, and R. Moussa. 2001. Herbicide transport to surface waters at field and watershed scales in a Mediterranean vineyard area. J. Environ. Qual. 30:982–991.

McDonald, L., S.J. Jebellie, C.A. Madramootoo, and G.T. Dodds. 1999. Pesticide mobility on a hillside soil in St. Lucia. Agric. Ecosyst. Environ. 72:181–188.

Ng, H.Y.F., J.D. Gaynor, C.S. Tan, and C.F. Drury. 1995. Dissipation and loss of atrazine and metolachlor in surface and subsurface drain water: A case study. Water Res. 29:2309–2317.

Poulenard, J., P. Podwojewski, J.-L. Janeau, and J. Collinet. 2001. Runoff and soil erosion under rainfall simulation of Andisols from the Ecuadorian *Paramo*: Effect of tillage and burning. Catena 45:185–207.

Rawlins, B.G., A.J. Ferguson, P.J. Chilton, R.S. Arthurton, J.G. Rees, and J.W. Baldock. 1998. Review of agricultural pollution in the Caribbean with particular emphasis on small island developing states. Mar. Pollut. Bull. 36:658–668.

Saison, C., P. Cattan, X. Louchart, and M. Voltz. 2008. Effect of spatial heterogeneities of water fluxes and application pattern on cadusafos fate on banana cultivated andosols. J. Agric. Food Chem. 56:11947–11955.

Sansoulet, J., Y.M. Cabidoche, and P. Cattan. 2007. Adsorption and transport of nitrate and potassium in an Andosol under banana (Guadeloupe, French West Indies). Eur. J. Soil Sci. 58:478–489.

Taylor, M.D., S.J. Klaine, F.P. Carvalho, D. Barcelo, and J. Everaarts. 2003. Pesticide residues in coastal tropical ecosystems: Distribution, fate and effects. Taylor & Francis, New York.

Thurman, E.M., D.A. Goolsby, M.T. Meyer, and D.W. Kolin. 1991. Herbicides in surface waters of the Midwestern United States: The effect of spring flush. Environ. Sci. Technol. 25:1794–1796.

Wada, K. 1989. Allophane and imogolite. p. 1051–1087. *In* J.B. Dixon and S.B. Weed (ed.) Minerals in soil environments. SSSA, Madison, WI.

Wada, K., and Y. Okamura. 1980. Electric charge characteristics of Ando A1 and buried A1 horizon soils. J. Soil Sci. 31:307–314.

Zheng, S.Q., J.F. Cooper, L. Palcy, C.M. Coste, and P. Marnotte. 1994. Mobility and dissipation of cadusafos in banana fields in Martinique. Sci. Total Environ. 156:1–9.